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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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THE CAROLINA BAYS

BY GERALD R. MAC CARTHY

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INTRODUCTION

General interest in the Carolina Bays was aroused, in 1933, by the publication of a paper by Melton and Schriever,[1] in which they suggested that these features were formed by a shower of meteorites. During the past three years, members of the Department of Geology of the Univer-

[1] F. A. Melton and William Schriever: *The Carolina "Bays"—are they meteorite scars?* Jour. Geol., vol. 41 (1933) p. 52-66.

sity of North Carolina have spent some time investigating these bays,[2] although only one major report has been published.[3] In that paper, Prouty summed up present knowledge concerning these puzzling features. He pointed out that:

(1) The bays are found only on the Coastal Plain between the Savannah River and Norfolk, Virginia; they are most common near the North Carolina-South Carolina border.

(2) Both bays and lake basins are elliptical, the major axes of the ellipses exhibiting a remarkable degree of parallelism.

(3) The major axes of these ellipses all trend in a northwest-southeast direction despite the changing trends of the coast line.

(4) The sand rims outlining the bays and lake basins are highest and best developed at the southeast ends of the bays. If multiple rims are present, they likewise occur only at the southeast ends.

(5) There is little or no correlation between the location of the bays and the topography, except that bays are not found along river flats and other areas of recent alluvium.

(6) The bays along the inner and along the outer margins of the Coastal Plain are equally well developed, which fact suggests that all are about the same age.

(7) Every bay and elliptical lake so far examined is associated with a distinct magnetic "high" southeast of the depression. Some of these highs are scarcely detectable; others are very marked. In general, they are more pronounced along the inner than along the outer margin of the Coastal Plain.

(8) In almost every case the high is slightly to the east of south of the southeastern end of the bay and at a distance about equal to the minor axis of the bay.

SUGGESTED THEORIES OF ORIGIN

In their original paper, Melton and Schriever accept a meteoritic theory as the best working hypothesis, but expressly leave the question open to further discussion. In a later paper, Melton[4] suggests that if the meteoritic theory is shown to be untenable, some form of submarine scour should be considered.

Cooke[5] thinks that the bays have been formed by rotary currents generated in long and narrow lagoons by prevailing winds, and a somewhat

[2] Field work by William F. Prouty and G. R. MacCarthy, assisted at various times by A. J. Alexander and H. W. Straley, III.

[3] W. F. Prouty: *Carolina Bays and elliptical lake basins*, Jour. Geol., vol. 43 (1935) p. 200-207.

[4] F. A. Melton: *Reply to "Discussion of the origin of the supposed meteorite scars of South Carolina"* (by C. Wythe Cooke), Jour. Geol., vol. 42 (1934) p. 97-104.

[5] C. W. Cooke: *Discussion of the origin of the supposed meteorite scars of South Carolina*, Jour. Geol., vol. 42 (1934) p. 88-96.

similar theory has been suggested by Johnson,[6] who supposes that they were formed by wind-driven waves acting on the sandy shores of fresh-water ponds that occupied initial depressions in a beach plain. These lagoon and pond theories seem to have been suggested by one or two rectilinear groups of bays in the Myrtle Beach area. Both Cooke and Johnson contend that these alignments are governed by beach ridges, and that, therefore, the beach ridges are an essential factor in the development of the bays. The Myrtle Beach region is the only one for which a large scale aerial mosaic is available, and until they are available for other regions it seems necessary to reserve decision on this point. However, this much can be said in regard to the Myrtle Beach area: only a few alignments are found even where beach ridges are present, whereas bays are common where no beach ridges are to be seen.

It is difficult to account for the elliptical shape and the almost perfect orientation of these bays on any theory based upon submarine scour. The bays are absent from the narrow strip of recently uplifted land that lies just inland from the beach, where submarine scour would presumably have been effective most recently. On the contrary, they are found along the inner margin of the Coastal Plain where recent submergence is out of the question. Nor does the fact that they are confined to a relatively small portion of the Coastal Plain seem favorable to such a hypothesis; if due to submarine scour, they should be found on many recently emerged coastal plains.

Other theories that have been suggested verbally, but have seldom, if ever, appeared in print, include:

(1) Sink holes. Several sinks are known in this general region (e. g., The Magnolia Wells, near Magnolia, North Carolina), but none of them bears any resemblance to the bays. It is difficult to understand how any type of sink-hole development could give rise to depressions that are smoothly elliptical in outline and possess such remarkable parallelism of orientation.

(2) Artesian springs. Several of the elliptical lakes seem to have artesian springs on their bottoms (e. g., White Lake), but the shape, the orientation, and the great number of bays seem to rule out any possibility of their being "wash-outs" caused by such springs.

(3) Salt domes. The solution of a salt plug or of the limestone cap rock of a salt dome might produce a circular or oval depression, but the shape and orientation of the bays are not consistent with such an origin. No salt domes are known on the Atlantic Coastal Plain, nor are such bays known on coastal plains where salt domes are fairly common.

[6] Douglas Johnson: *Origin of the Carolina Bays* [abstract], Geol. Soc. Am., Pr. 1935 (1936) p. 84.

(4) Sand dune "blow-outs." The regularity in shape and orientation of these bays is not consistent with this theory, nor has any eolian cross-bedding been observed in any of the sand rims. If due to such blow-outs, bays should be found in many regions of sand dunes, and such is far from the fact.

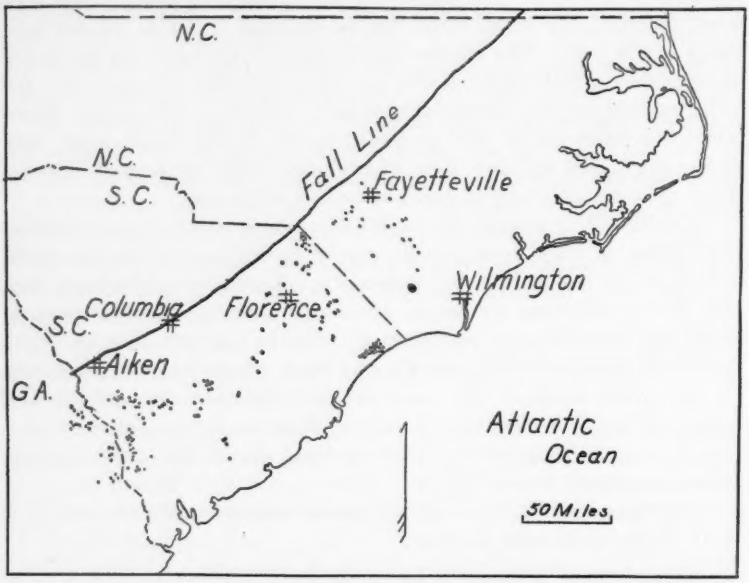

FIGURE 1.—*Sketch map showing location of definitely known bays*

The bays shown are a small fraction of those that exist in this general area; many cannot be found except by examination of aerial photographs, and these are available for only a small portion of the total area. Redrawn from a map compiled by W. F. Prouty.

It is not proposed to discuss these alternative theories in detail, for this has been done in the papers already referred to, but to suggest a logical theory based on the meteoritic hypothesis, which, in the opinion of the writer, is the best working hypothesis so far proposed.

METEORITIC HYPOTHESIS

GENERAL STATEMENT

Any hypothesis that seeks to explain the origin of these bays must explain the following facts: The bays occupy only a restricted area; they possess a parallel orientation; they are smoothly elliptical in outline; some of them intersect; they show little or no correlation with topography; they are equally well developed on the inner and on the

outer margins of the Coastal Plain; and they are associated with localized magnetic highs. These facts all follow as a matter of course from a consideration of the type of meteoritic hypothesis here proposed.

MAGNETIC HIGHS ASSOCIATED WITH THE BAYS

Several thousand magnetic observations made on the Coastal Plain of the two Carolinas have disclosed many magnetic anomalies in this area.

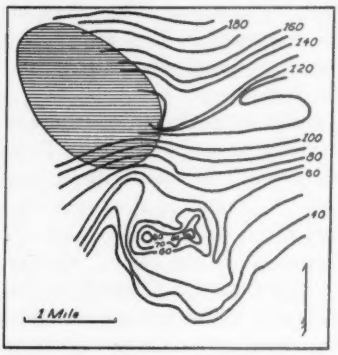

FIGURE 2.—*Isogamic map of the magnetic high associated with the large bay just west of Syracuse, South Carolina*

The magnetic slope north of the high is the south flank of a large magnetic "ridge" which is a regional feature. Contour interval 10 gammas. Redrawn from a map by W. F. Prouty.

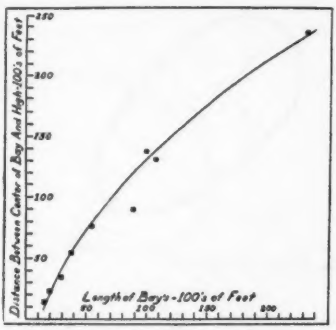

FIGURE 3.—*Diagram showing the relation between the length of the major axes of nine typical bays and the distance from the center of each bay to the center of the associated high*

The equation of the smooth curve is:
$X = 0.0028Y^2 + 0.3Y + 13.4$.

Two classes of such anomalies have been distinguished. One, the "linear" type, consists of a narrow belt, in many places only 100 feet wide, in which the magnetometer readings are either well above or well below the regional average. Many such linear "highs" and "lows" may be traced for miles, and seem to have no connection with the bays; their general trend is northeastward. They seem to be caused by structural features of the crystalline rocks beneath the Coastal Plain sediments.[7] The other type of anomaly is the "point high" and consists of a restricted and more or less circular area in which the magnetometer readings are above the regional average. As far as is known, this type of anomaly is found on the Coastal Plain only in connection with the bays. They are entirely unrelated to the linear highs, although both may be found in the same locality. In one place, point and linear highs have been found to over-

[7] G. R. MacCarthy: *Magnetic anomalies and geologic structures of the Carolina Coastal Plain*, Jour. Geol., vol. 44 (1936) p. 396-406.

lap. Near the village of Syracuse, South Carolina, a particularly well-developed bay was found to be situated directly over the crest of a pronounced linear high. The point high associated with this bay lay on the south flank of the linear high, so that the isogams outlining it were not closed curves, but were in the form of an open nose or terrace (Fig. 2).

Each bay investigated is associated with one of these point highs, but it cannot be stated that each point high of the Coastal Plain is associated with a bay. The proof of such a relationship would be a strong confirmation of the meteoritic hypothesis.

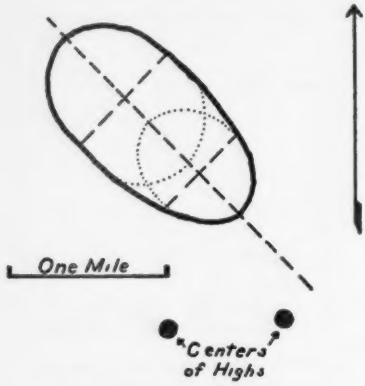

FIGURE 4.—*Sketch map of Singletary Lake*

Arrow indicates magnetic north.

Prouty states that in most places the magnetic highs occur "a little east of south of the southeast end of the . . . bay . . . and at a distance about equal to the short diameter . . . of the bay."[8] One or two highs were not found in the expected position, but even in such cases there seems to be a definite relation between the size of the bay and the distance between its center and the center of the high. In Figure 3, the measurements for nine well-developed bays are plotted against each other. The closeness with which the resulting points conform to a smooth curve indicates a genetic connection between the bays and the highs. Two of the highs used in drawing this figure are associated with Singletary Lake. Singletary Lake is more elongate than are most of the elliptical basins and probably, as is suggested by the dotted lines of Figure 4, consists of two overlapping bays. This supposition is confirmed by the discovery of two distinct highs in the exact position demanded by Prouty's rule.

LOCATION OF THE METEORITES

It has been generally assumed that, if these bays are really meteorite scars, their ellipticity was caused by the meteorites striking the earth at an oblique angle, and that the angle of impact might be calculated from the observed eccentricity of the ellipses that outline the bays. It has been further assumed that the trend of the major axes of these ellipses indicates the direction (referred to the surface of the earth) in which the meteorites were moving at the moment they struck the earth. The magnetic data do not agree with either of these assumptions.

[8] W. F. Prouty: *op. cit.*, p. 202.

From the principle of magnetometric surveying,[9] it may be shown that in the northern hemisphere any object causing a magnetic high must lie due north (magnetic north) of the center of the high which it produces. If the object is a sphere, or is approximately equidimensional, it may be shown that the southward displacement of the high will be (in the latitude of the Carolinas) approximately one-tenth of the depth to the magnetic object. Thus, a magnetic mass buried at a depth of one mile would produce a high whose center would lie about one-tenth of a mile south of a point directly above the buried mass.

On the assumption that the bays were formed by meteorites that continued their underground course along a path lying in the vertical plane that includes the major axis of the bay, and that the point highs are caused by the presence of meteoritic material, this material would lie directly beneath the intersection of a line drawn due north from the center of the high and a line marking the prolongation of the major axis of the bay; that is, at point "M" of Figure 5. If this were true, the depth to the buried meteorite might be computed in either one of two ways. As the high caused by such a meteor must lie due south of it, and at a distance of one-tenth the depth of burial, the meteorite would lie directly under point "M" and at a depth equal to ten times the distance M—H. This depth might also be computed by trigonometric methods from the calculated angle of impact and the distance O—M, for it is equal to O—M times the tangent of the angle of impact. Such computations produce discordant results, the depths derived from the magnetic formula being from two to sixteen times the depths derived by the trigonometric

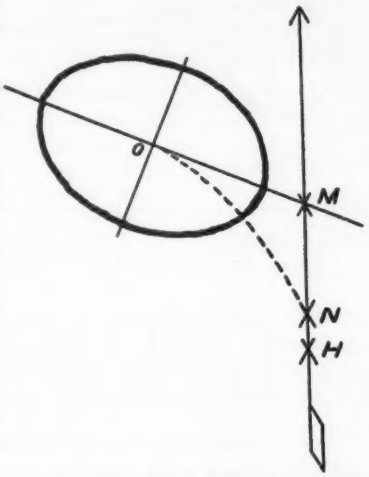

FIGURE 5.—*Sketch showing relation between a typical bay and its associated high*

Arrow indicates magnetic north, O marks the center of the bay, H is the center of the associated high, M is the intersection of a prolongation of the major axis of the bay with a north-south line drawn through the center of the high, and N is the probable position of the object producing the high.

[9] The instrument used in this work was a Schmidt type vertical field balance made by the Askania Werke.

method. Obviously the meteor cannot lie directly beneath point "M," for, if it did, the two formulae would give concordant results.

If the assumption is made that the meteor did not continue its underground course with azimuth parallel to the major axis of the bay, but that it followed a course such as is indicated by the dotted line O—N

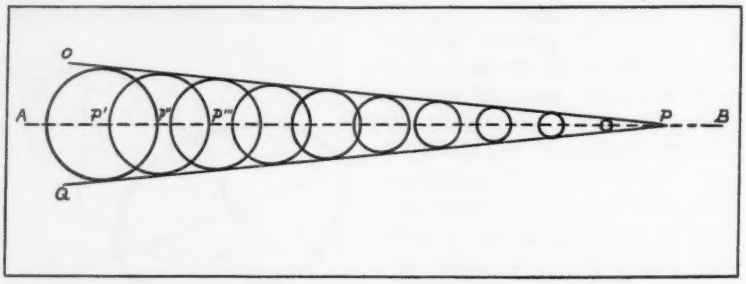

FIGURE 6.—*Diagram of the conical shock-wave produced by a spherical projectile moving along path A—B with a velocity ten times that of sound in air*

of Figure 5 and is situated at some point "N," more concordant results are obtained. Other much less accurate calculations based on the observed width of the highs also indicate that the masses producing them must lie beneath some point not far north of "H."

FORMATION OF THE BAYS BY AERIAL SHOCK-WAVES

The bays and lake basins vary greatly in size. Lake Waccamaw, which seems to be the largest, is about 5 miles long; many of the smaller bays are only a few hundred feet in greatest diameter. Scars produced by meteorites would vary in size according to the size of the meteorites, but in any case the meteorite would be much smaller than the crater it produced in incoherent material, because such a crater would be not a simple "bullet hole," but the result of the air-blast accompanying the meteorite. When a high-powered bullet is fired into a pan of loose dust the air waves accompanying it blast out a shallow crater whose diameter is from ten to twenty times that of the projectile.

Any object moving through the air with a velocity greater than that of sound is the apex of a cone of highly compressed air, technically known as a "shock-wave." This cone of compressed air is the envelope of a family of spheres whose respective centers mark the position of the projectile at successive instants, and whose radii are equal to the distance traveled by a sound wave since the instant when the projectile occupied the points marking their centers. Figure 6 illustrates the shock-wave

accompanying a projectile whose velocity is ten times that of sound.[10]

The conical wave-front of such a shock-wave moves outward in a direction perpendicular to itself with the velocity of sound in air. This velocity is, under normal circumstances, about 1100 feet per second, but increases with increasing pressure. Therefore, the shock-wave produced by a large meteorite might have a velocity somewhat in excess of this

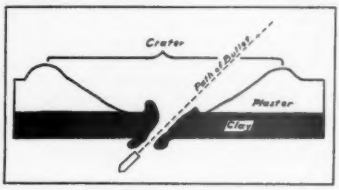

FIGURE 7.—*Cross-sectional diagram of the crater produced by firing a high-speed bullet into a pan filled with loose plaster of paris powder which rested upon modeling clay*

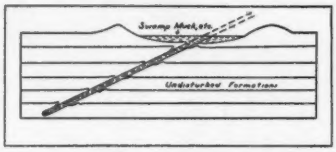

FIGURE 8.—*Hypothetical cross-section of a bay formed by the shock-wave accompanying the infall of a large meteorite*

A crater has been blown out of the uppermost formation, while the underlying ones are essentially undisturbed except for the small "bullet-hole" which has been drilled through them.

figure, for the air would be intensely compressed. The velocity of the wave of compression caused by an explosion is also 1100 feet per second, so that such a shock-wave would have a truly explosive effect. An explosion has a point source, and its intensity at any distance from its source varies in accordance with inverse square law, whereas a shock-wave, having a linear source, varies in intensity inversely with the distance itself. That is, as an explosion wave travels outward in the form of an expanding sphere, its intensity at a given distance from the site of the explosion will vary inversely with the square of the distance; whereas the intensity of a shock-wave, whose form is that of an expanding cone, would vary inversely with the distance from the axis of the cone. In other words, at a given distance from the source of the disturbance, a shock-wave would have an effect similar to, but more intense than, that of an equivalent explosion.

Experiments made by firing high-speed bullets into pans filled with loose dust indicate that a bay a mile or more in diameter might be formed by the shock-wave accompanying the fall of a meteorite not more than

[10] Aerial shock-waves are described rather fully in the following papers, among others:

William Payman and D. W. Woodhead: *Explosion waves and shock waves*, Royal Soc. London, Pr., vol. 132 (1931) p. 200-213.

P. S. Epstein: *The air resistance of projectiles*, Nat. Acad. Sci., Pr., vol. 17 (1931) p. 532-547.

G. I. Taylor and J. W. McColl: *The air pressure on a cone moving at high speeds*, Royal Soc. London, Pr., vol. 139 (1933) p. 278-311.

Encyclopedia Britannica, 14th ed., vol. 21, p. 22, article headed *Explosion waves* (*Onde de Choc*).

300 or 400 feet in diameter. Figure 7 is a cross-sectional diagram of such an experiment. A large wooden tray was partly filled with modeling clay over which was spread about 3 inches of dry plaster paris, and

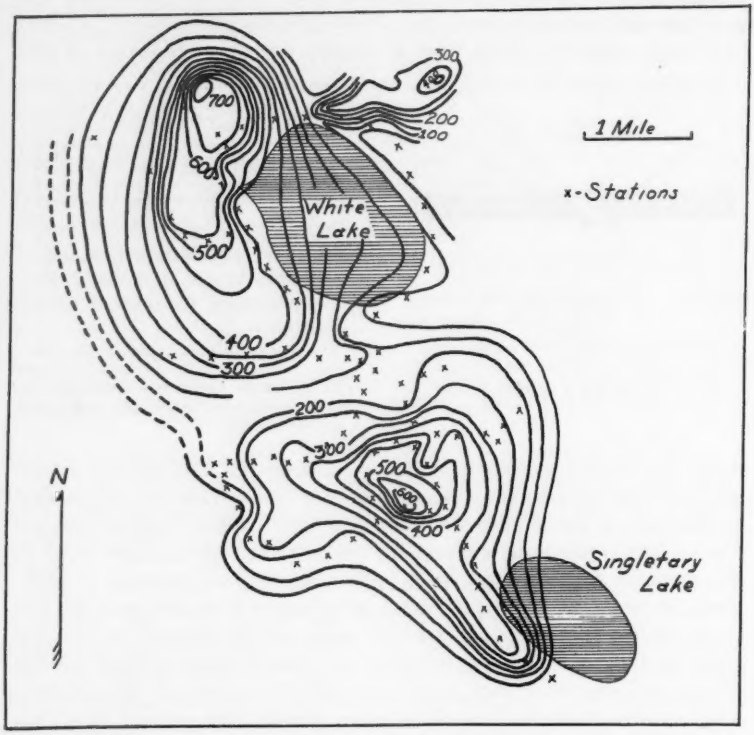

FIGURE 9.—*Sketch map showing a typical bay with its associated high*

White Lake is the bay, and the high associated with it is roughly heart-shaped and lies to the southeast. The large high whose center is northwest of White Lake is associated with a much larger bay which does not appear on the map. Contour interval 50 gammas. Crosses mark the positions of the magnetometer stations. Redrawn from a map by W. F. Prouty.

a 30-30 bullet was fired into it from a distance of about 20 feet. Much plaster and a small amount of clay were thrown upward and outward by the explosive action of the shock-wave, so that a crater of considerable size was produced.

If the bays were formed by these aerial shock-waves, they are much larger than the meteorite producing them, and should be floored by undisturbed sediments, except for the small "bullet hole" drilled by the meteorite itself. Any drilling operations carried out in them should dis-

close undisturbed formations, unless the drill hole happened to be in exactly the right spot. Figure 8 is a hypothetical cross-section of a bay illustrating this point.

That the fall of a large meteorite or cluster of meteorites would produce effects analogous to those produced when a high-speed bullet is fired into loose dust is shown by the following account of the unique Siberian fall of 1908.[11]

"In the central area, perhaps 2 miles in diameter, there was a sort of shallow depression, the ground showing signs of being violently pushed side-wise as when a stone is dropped into thick mud so that ridges could be seen. Inside this area were 200 shell-holes or craters varying from 1 to 50 yards in diameter. In this central area all trees had been destroyed, and over an area of 30 to 40 miles in diameter they were to be found by the tens of thousands, lying with their tops away from the center, and seared as though touched by the heat from a giant blow torch."

The "shallow depression" 2 miles in diameter seems to correspond to one of the Carolina Bays, and the 200 "shell holes" to a similar hole or holes in the floor of the bay, now covered by swamp muck and sand. The depression noted in the case of the Siberian fall and the destruction of the forests were undoubtedly caused by the shock-wave of intensely compressed and highly heated air which accompanied the meteorites. To continue:

"A native, 'three days march' from the place, had his hut knocked down, the top blown away by the wind, his brother stunned, and his herd of reindeer scattered. A man at a distance of over 30 kilometers described it thus: '. . . there appeared a kind of fire which produced such a heat that I could not stand it. . . . I had only time to lift my eyes and it was gone. . . . Then it became dark, and then followed an explosion which threw me down from the porch about six feet. . . . I heard a sound as if all the houses would tremble and move away. Windows were broken, a strip of ground torn away, and an iron bolt on the warehouse broken'."

Both on the Siberian tundra and on the Carolina Coastal Plain there are thick layers of incoherent material which were readily moved by the shock-waves. Such unconsolidated material is lacking on the Piedmont and other "hard rock" areas, so that craters of this sort could not be formed except perhaps along the river bottoms, where they would soon be destroyed by stream action; hence their absence from such areas.

DIVERGENCE BETWEEN THE PATH OF THE METEORITE AND THE AXIS OF THE BAY

It has already been stated that the magnetic data did not agree with the assumption that the trend of the major axis of a bay indicated the direction of travel of the meteorite producing it, for in almost every case investigated the high was located well to the south of the line marking the prolongation of the axis of the bay (Fig. 5). If the bay is the result of a conical shock-wave, the major axis of the bay should certainly agree with the azimuth of the axis of this cone. As the path of the meteorite through the air would coincide with the axis of the cone, any divergence

[11] C. P. Oliver: *Comets* (1930) p. 198-206. Williams & Wilkins, Baltimore.

between them must have occurred after the meteorite penetrated the ground. It is difficult to explain such a divergence, but the magnetic data indicate clearly that it took place. Any spin of the meteorite about its own axis would produce some curvature of path (as with a "curved ball" thrown by a pitcher), and the rotation of the earth about its own axis would introduce further curvature. The former effect would vary with the individual spins of the different meteorites, and could scarcely be uniform from bay to bay, but the latter, depending only upon the rotation of the earth and the linear velocity of the meteorites, would be more uniform. In the northern hemisphere the effect of the earth's rotation about its axis is to cause any moving object to be deflected to its own right by an amount proportional to the velocity of the object and to the sine of the latitude, and such a deflection would be in the proper direction to throw the meteorites to the south of the prolongation of the major axis of the bays. Qualitatively, there is little difficulty in thus explaining the observed divergence between the paths of the meteorites and the axes of the bays, but a quantitative check is another matter. This right-hand deflection is indicated in Figure 5, by drawing the horizontal projection of the supposed underground path of the meteorite as a curve concave toward the southwest.

THE ENERGY OF LARGE METEORITES

No authentic meteorites seem to have been collected in the vicinity of the great Siberian fall of 1908, although the natives of the region state that pieces of iron have been picked up in the central area of the fallen forest.[12] Either the meteoritic material was buried in the muck of the tundra or it was volatilized when its energy of motion was changed into heat. In the former case the burial cannot be deep, for, if the kinetic energy was sufficient to cause deep penetration into the earth, it was also sufficient to cause complete volatilization. As no mention seems to have been made of fused rock or soil, it appears likely that the Siberian meteorite was moving at a relatively low velocity and had comparatively little energy. In this case, it cannot have penetrated the ground deeply, and magnetic investigations in the neighborhood of the craters might be fruitful.

The Carolina Bays are like the Siberian craters in that neither meteoritic material nor fused rock has been reported. In other examples of meteoritic craters, notably the Wabar craters of Arabia,[13] both fused

[12] L. J. Spencer: *Meteorite craters as topographical features on the earth's surface,* Geogr. Jour., vol. 81, no. 3 (1933) p. 227-248. This paper has been reprinted in several places, including the Smithsonian Annual Report for 1933. In this reprint the discussion accompanying the original paper was omitted, but an additional note of the evidence of the development of great heat was added.

[13] H. St. John Philby: *Rub' Al Kali . . .*, Geogr. Jour., vol. 81 (1933) p. 1-26.

rock and meteoritic fragments are known. In still other examples, as at the craters near Henbury, Australia, and near Odessa, Texas,[14] meteoritic iron has been found but silica glass is scarce (Henbury) or lacking (Odessa). In view of this, it cannot be said that a lack of such material in connection with the Carolina Bays is an insurmountable objection to the meteoritic hypothesis.

The kinetic energy of a large meteorite (as distinct from that of its shock-wave) traveling with a speed in excess of that of sound would be largely expended in punching a hole into the earth. This energy would all be liberated locally in the form of heat until the velocity of the meteorite fell to less than that of sound in rock or, roughly, about 5 miles per second. As the least probable velocity that can be assigned to such a meteorite is about 7½ miles per second,[15] the meteorite and much of the solid material with which it came in contact would necessarily be volatilized. Aside from such fragments as might be blown backward by explosions of the main mass, and hence have their velocity checked sufficiently to prevent complete volatilization, the only meteoritic remains to be expected would be condensations of this volatilized material. A certain amount of vapor would certainly condense in the hole punched out by the meteorite; this could easily be the cause of any magnetic effects observed.

Atmospheric resistance would check the velocity of small meteorites, but would not appreciably affect that of masses of many tons. If it be assumed that half of the heat generated by impact with the earth is available for heating the meteorite—the other half being dissipated into the earth—it may be shown that an iron meteorite striking the earth with a velocity of only 4 miles per second would be completely volatilized. (The critical velocity for a stony meteorite would be of the same order of magnitude.) This is, as has been stated, much less than any probable velocity that can be assigned to large meteorites, and hence it must be concluded that such large masses would suffer complete volatilization. Spencer presents evidence of such volatilization.[16] He says:

"Further evidence is forthcoming that very high temperatures prevailed at the time the crater was formed. The meteoric iron was vaporized in large amounts and

[14] L. J. Spencer: *op. cit.*, p. 230, 231-232.

[15] The parabolic velocity of celestial objects at the earth's orbit is about 26 miles per second, whereas the velocity of the earth in its orbit is about 18.5 miles per second. If the earth and the meteorite met "head on" the velocity of the latter in respect to the earth would be 26 plus 18.5, or 44.5 miles per second, but, if the meteorite overtook the earth, the corresponding velocity would be the difference of these values, or 7.5 miles per second.

[16] Note added to reprint of Spencer's paper in the Smithsonian Annual Report for 1933. *See* also:

A. R. Alderman: *The meteorite craters at Henbury, central Australia,* Mineral. Mag., vol. 23 (1933) p. 19-32 and:

L. J. Spencer: *Meteoric iron and silica glass from the meteorite craters of Henbury and Wabar,* Mineral. Mag., vol. 23, no. 142 (1933) p. 387-404.

condensed as minute spheres; those which fell into the boiling silica were preserved. Some of the vesicular silica glass from Wabar is estimated to contain as many as 2,000,000 of these minute polished spheres of nickel-iron per cubic centimeter."

The Wabar meteorite fell into sand, and large quantities of silica glass were developed. The Henbury meteorites penetrated sandstone and "slaty rock" and developed little glass. The surface material of the Carolina Bays is largely sand, and one might expect to find considerable development of silica glass in connection with them; none has as yet been reported. In Siberia, no fused material has been reported, although the forest was ignited for miles around. If the greater portion of the total energy released by the Siberian and Carolina meteorites went into aerial shock-waves and only a small portion was carried into the ground, these facts might be more easily explained. Whipple [17] has computed that, at the time of the Siberian fall, five thousand times as much energy went into air-waves as went into seismic waves. (No figures are given as to the proportion of the total energy changed into heat.) If a similar partition of energy prevailed during the fall of the Carolina meteorites the lack of visible evidences of fusion is more understandable. It is true that a tremendous amount of energy would be contained in the shock-waves, but it would be spread over a large area and dissipated at a relatively low rate and, therefore, might not produce temperatures sufficient to fuse silica, although the adiabatic compression of the air would raise its temperature enough for the ignition of inflammable substances, as in Siberia. On the contrary, the energy retained by the meteorite itself would be liberated locally and at an extremely high rate. Under these circumstances, it would be so concentrated in space and in time that the meteorite would be volatilized and the rocks with which it came in contact would be fused and perhaps volatilized. However, this would take place only in the immediate vicinity of the hole punched out by the meteorite, and would not affect the sand rims formed by the explosive action of the shock-waves. But the meteorite hole lies in the bottom of the bay near its center and is at present concealed by the filling of swamp muck and sand. Neither this hole nor the silica glass would be found during an ordinary examination of the bay; they would be revealed only by thorough excavation or by a drill-hole situated in exactly the right spot.

It is by no means clear just what conditions are necessary for such a one-sided partition of energy; however, such conditions did prevail at the time of the Siberian fall, and there is no reason to assume that they did not also prevail when the Carolina Bays were formed.

[17] F. J. W. Whipple: *The great Siberian meteor and the waves, seismic, and aerial, which it produced*, Royal Meteorol. Soc., Quart. Jour., vol. 56 (1930) p. 287-304.

TESTS OF THE SHOCK-WAVE THEORY

If the theory here outlined is sound, it should be capable of proof. Should several typical bays be carefully excavated, or explored by means of closely-spaced bore holes, this proof might be obtained. Undisturbed or only slightly disturbed sediments would be found beneath the bay except at the "bullet-hole" made by the meteorite. This point alone would probably be marked by the development of silica glass. Ferruginous material, either actual meteoritic fragments, or materials derived from them by weathering, would be found in the appropriate location. The theory might likewise be disproved if it can be shown that it is not consistent with the laws of physics, or if "bullet-holes" can be shown to be absent from the floors of the bays.

This theory is presented only as a working hypothesis, and if a more plausible theory can be constructed to explain the known facts, the writer will be the first to cast aside the present theory or relegate it to second place.

CONCLUSIONS

Present evidence seems to support the theory that:

(1) The Carolina Bays were formed by the shock-waves accompanying a shower of large meteorites, and not directly by the impact of the meteorites upon the earth.

(2) The bays are much larger than the meteorites that produced them.

(3) The great Siberian meteorite of 1908 produced effects similar to one of the Carolina Bays, and, had a shower of such meteorites fallen, a series of bay-like depressions would have resulted.

(4) It is probable that the meteorites were largely or wholly volatilized by the heat developed when their motion was checked.

(5) The magnetic highs associated with the bays are caused by the presence underground of meteoritic material. This material may be, in part, actual fragments, or may be condensations from the vapor formed when the meteorites volatilized.

(6) The underground courses of the meteorites were not straight lines, but curved in such a fashion as to be, in horizontal projection, concave toward the southwest. The deflective effect of the earth's rotation furnishes a qualitative, but perhaps not a quantitative, explanation of this curvature.

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ALGAE AND ALGAL LIMESTONE FROM THE OLIGOCENE OF SOUTH PARK, COLORADO

BY J. HARLAN JOHNSON

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INTRODUCTION

Algal limestones were obtained from a number of localities in the course of a study of the geology of South Park made in the summers of 1934 and 1935 under the sponsorship of Northwestern University and assisted in 1935 by a grant from the Penrose Bequest of the Geological Society of America. The geology and stratigraphy of the region including a brief mention of the algal limestone are being given in a general report shortly to be published.[1] The present paper is intended to give a more detailed description of the algal limestones, their distribution, structure, and conditions of deposition, and of the algae which assisted in their formation.

The author wishes to thank Professor C. H. Behre, of Northwestern University, for many courtesies extended in the course of the work. He also wishes to thank Dr. F. M. Van Tuyl and W. A. Waldschmidt, of the Colorado School of Mines, and Dr. Francis Ramaley, of the University of Colorado, for assistance and criticism, Mr. W. H. Bradley, of the United

[1] J. T. Stark, J. H. Johnson, C. H. Behre, W. E. Powers, A. L. Howland, and D. B. Gould: *The geologic history of South Park, Colorado.*

States Geological Survey, for the loan of his slides and type specimens of Green River material and for his valuable criticism of the manuscript. Mr. Hugo Rodeck, of the University of Colorado Museum, photographed the specimens used as illustrations.

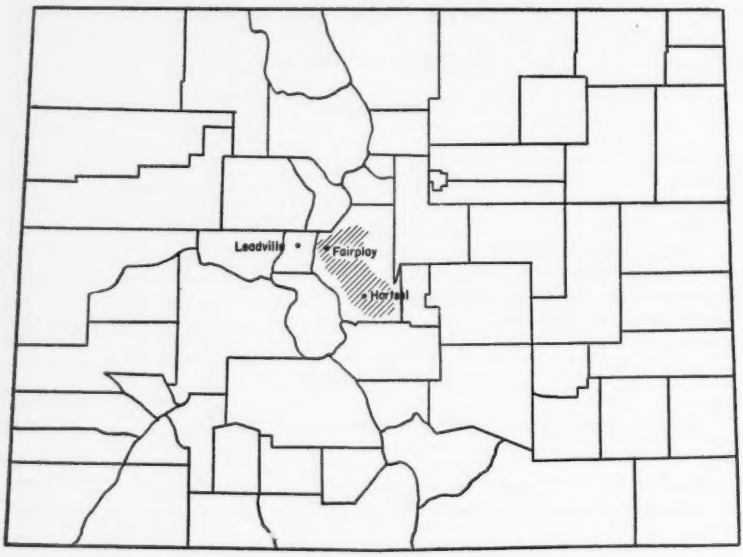

FIGURE 1.—*Outline map of Colorado showing location of South Park*

LOCATION

South Park is a basin-like depression in central Colorado lying between the Mosquito Range and Arkansas Hills on the west, the Front Range and related mountains on the east, and the Kenosha Hills, Tarryall Mountains, and the continental divide on the north (Fig. 1). It lies mainly in Park County.

The algal limestones occur among the lake deposits of Oligocene age which constitute the main portion of the Antero formation. These deposits were laid down in several long, narrow, partly connected lake-basins in pre-Cambrian rocks along the eastern side of South Park, lying in T. 10 and 11 S., R. 74 and 75 W., and in a larger basin which covered much of the southern half of the present park area in T. 12 to 16 S., R. 75 and 76 W. Outcrops of the limestone showing good algal structure can easily be obtained along the road in the southwest corner of Sec. 13, T. 13 S., R. 76 W.

ALGAL LIMESTONES

PETROGRAPHY

On weathering, the algal limestones appear gray to white. Specimens of fresh material, however, range from pale yellowish white to rich brown. Locally they are porous, practically a calcareous tufa; some are dense. Some beds show fairly good stratification with breaks of shale or volcanic ash. Others show little or no indication of bedding. At some localities the algal origin is quite evident.

The original deposit was a very porous calcareous tufa. Very shortly after deposition, however, deposition of calcite filled much or all of the included space, and quite probably this took place in the lower part of a deposit while the upper surface was still covered by living algae. As a consequence of the filling of the spaces and some later crystallization, the resulting rock is usually quite dense and tough.

Silicification has occurred at many places. This may be slight or practically complete. At a few places there was perfect replacement of the original structure—Plate 1, fig. 1 shows a piece 91 per cent SiO_2. More often, however, replacement is only partial and much of the original structure has been obliterated. Locally some solution occurred before or during silicification and the rock contains vugs and irregular cavities filled with botryoidal chalcedony. Where silicification is nearly complete the rock appears as a white or light-gray chert containing patches, vugs, and stringers of chalcedony, or it may have become a mass of nearly translucent chalcedony with irregular opaque streaks and patches. These completely silicified masses show no evidence of original structure and present no clues as to origin. Fortunately, however, the partly silicified masses are surrounded by the completely altered, or in other localities a bed of completely silicified rock may be traced along the outcrop to unaltered limestone.

Fragments shown in Plate 1, fig. 1, and Plate 2, fig. 1, were analyzed by F. C. Schroder, of the Colorado School of Mines Experimental Plant, and gave the following results:

	No. 1 (per cent)	No. 4 (per cent)
SiO_2	90.2	0.68
Al_2O_3	0.82	0.52
Fe_2O_3	2.58	0.43
CaO	3.2	54.4
MgO	0.51	0.72
CO_2	2.56	42.90
Organic matter	0.04	0.40
	99.91	100.05

GENERAL TYPES OF DEPOSITS

The algal deposits are of two types: (1) narrow, steep-sided, fringing reefs, and (2) wide-spread, flat beds.

The first type parallels the shores of the old lake. They are best developed along the sides of small bays or re-entrants. In the majority of the examples observed, the reefs rest directly upon the pre-Cambrian and form the first true lacustrine deposit laid down at the particular place. At some places, however, they rest on sandstones and shales. They vary from narrow ridges to irregular lenticular masses; the side away from the shore is usually the steeper. They range from 50 to more than 1000 feet long; from 4 to 55 feet thick; and from 5 to about 75 feet wide. Commonly, they are less than 250 feet long, are from 8 to 15 feet thick, and from 20 to 30 feet wide.

Deposits of this type were observed in the southwest quarter Sec. 1, SW ¼ Sec. 22, and in Sec. 23 of T. 10 S., R. 75 W.; in T. 11 S., R. 75 W., in Sec. 20, T. 13 S., R. 75 W., and in Sec. 36, T. 12 S., R. 76 W.

The bedded deposits are extensively developed in the southern part of the large lake basin south-southwest of Hartsel. They consist of wide-spread, more or less regular beds of limestone sandwiched between stratified shales, ostracod limestone, tuffs, and tufaceous sandstones. Individual beds range from a few inches in thickness to nearly 8 feet. They represent accumulations on the bottom of a shallow lake. Outcrops of some of these limestones were traced for 4 or 5 miles. Good examples of them may be seen in Sec. 30, T. 13 S., R. 75 W., and in Sec. 13 and 14, T. 13 S., R. 76 W.

The size and shape of the limestone masses seem to have been governed largely by the profile of the lake shore and the depth of the lake. Along steep, rocky shores fringing reefs occurred close to the shores while in wide shallow lakes bedded deposits developed over large areas of lake bottom. In this respect they resemble the Eocene and modern algal reefs described by Bradley.[2]

FORM AND STRUCTURE

Each reef is formed of great numbers of small dome-like masses. Some are shaped like small cabbages or puff-balls, whereas others are more complex. The simpler, cabbage-like forms are considered as individual algal colonies. They grew more or less separately, crowded together to form a rock suggestive of a coarse, porous pisolite (Pl. 1, figs. 1 and 2). Under other conditions, long lobed, finger-like or conical structures developed which are considered to represent compound colonies (Pl. 1, fig. 2; Pl. 2, figs. 1 and 2).

[2] W. H. Bradley: *Algal reefs and oölites of Green River formation*, U. S. Geol. Surv., Prof. Paper 154-G (1929) p. 206-207.

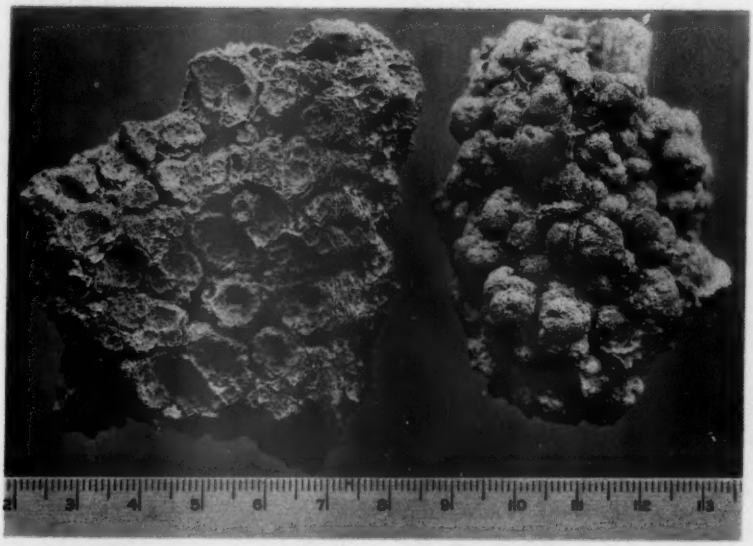

FIGURE 1. SILICIFIED ALGAL COLONIES
Bottom view (left), top view (right).

FIGURE 2. FINE-TEXTURED ALGAL LIMESTONE

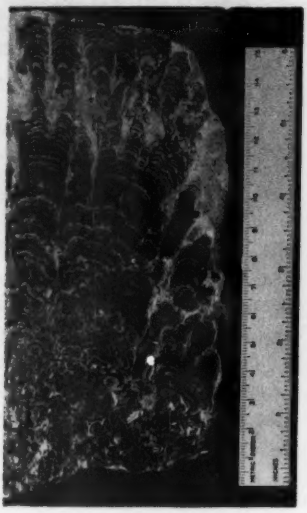

FIGURE 3. LONG ALGAL GROWTHS

ALGAL COLONIES AND LIMESTONE

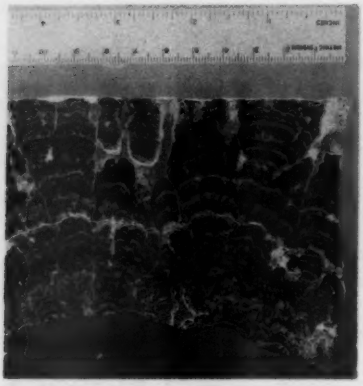

FIGURE 1. ALGAL LIMESTONE CUT PARALLEL TO GROWTH

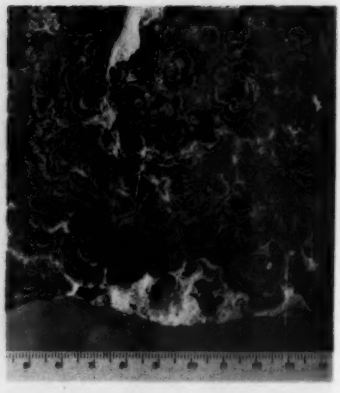

FIGURE 2. ALGAL LIMESTONE CUT PERPENDICULAR TO GROWTH

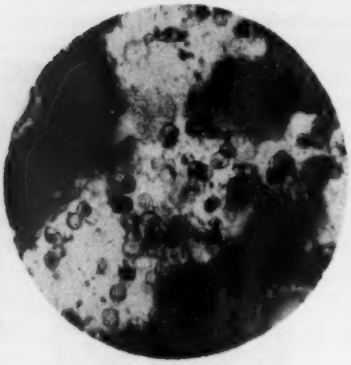

FIGURE 3. CELLULAR STRUCTURE *Oncobyrsella coloradoensis*
x 450.

FIGURE 4. CELLULAR STRUCTURE *Oncobyrsella coloradoensis*
Shows arching layers of small spherical cells.
x 32.

ALGAL LIMESTONE AND CELLULAR
STRUCTURE OF ALGAE

The simple colonies consist of a series of arched layers, alternately dense and porous. As the colonies become larger the layers become more strongly arched.

The compound colonies have steep, often overhanging, sides and arched top and bottom surfaces. The surfaces are either smooth or pustulate. Each compound colony is composed of arching layers of slightly irregular thicknesses. These layers seem originally to have been alternations of relatively dense and porous material. Some of these compound colonies grow to be 35 or 40 centimeters long and from 2 to 6 centimeters wide. Locally they branch into smaller ones. The space between the colonies is filled with silt, ostracods, and fine volcanic ash. Gastropod shells occasionally occur in the spaces or within the mass of the colony.

The thin arching layers in the colonies of both types probably represent growth stages, seasonal or annual. This is emphasized by the fact that a number of thin sections showed silt and foreign material to be consistently more abundant in alternate layers. One can picture a season of rapid growth when the algae formed a thin felt of unicells and fibres, each unicell or fibre coated with secreted calcium carbonate. A small amount of fine silt was washed in or dropped by the wind. Then came a season when growth stopped or slowed down. During this latter period probably some solution of the outer surface and recrystallization of material took place, along with the deposition of silt. Then came another season of rapid growth, and so on. Possibly a pair of layers represents a year.

The reason for the great development of simple colonies in some places and of compound colonies in others presents a problem. There are several possible factors: (1) a difference in kind or aggregation of kinds of algae present; (2) differences in conditions of growth, especially in the amount of silt and other foreign material being deposited during growth; (3) differences in the character of the bottom on which the algae grew; and (4) differences in depth and light.

How important the first factor might be was not determined in the present study. Probably, however, it does not matter, as Pia [8] has shown that under similar ecological conditions lime-secreting algae of all groups, blue-green, green, brown, and red, tend to produce colonial forms which are very similar in shape and general external appearance.

It must be remembered that the material here described really represents a pseudomorph of the algal colony or, perhaps more truly, imperfect molds and casts of the algae; it does not represent true fossil algae in the sense the words are used in the fossil red algae such as *Solenopora* or *Lithothamnium*, where not only the outward form and appearance of the colony is preserved but also the internal cellular structure. The reason

[8] J. Pia: *Die Anpassungsformen der Kalkalgen*, Palaeobiologica, vol. 1 (1928) p. 211-224, pl. 15-22.

for this has been clearly stated by Bradley in a description of the modern algal deposits of Green Lake, New York. He writes:

"if the calcium carbonate in the softer outer layer is dissolved in dilute acetic acid there remains a very dense felt of algae which retains the original dimensions and intricate form (of the algal lime deposit). Close to the surface, the calcium carbonate, in the form of minute granules 3 to 6 microns in diameter, partly fills the interstices between the algae filaments and unicells and thus makes a very imperfect cast of the interstices, or, stated differently, a mold of the plants. But because the algae are so densely entangled the resulting molds are those of groups or small felts of the plants rather than of individual plants. Only rarely in such complex assemblages of algae are the individual filaments or unicells so widely separated that recognizable molds of them are formed."[4]

The second factor, differences in conditions of growth, especially in the foreign material deposited during growth, probably was the most important. Wherever the simple colonies are found they occur as coatings on pieces of wood, on fragments of rocks, or on the rocky sides or bottoms of the lake—in other words, where the algae could grow freely, unhampered by depositing silt.

Where the bottom on which they grew was silt-covered, or in localities or times of active sedimentation, the complex type of colony developed. As the silt was deposited and settled in the spaces around and between the colonies, they had to grow upward to keep from being covered and to obtain light. If upward growth could not keep pace with deposition the colonies were soon covered and killed. The shape of the colonies agrees with this (Pl. 1, fig. 3); so does the way they pinch and swell and the way in which some colonies will stop and be covered by sediment, being followed a little higher by another new colony. Frequently different colonies start at different levels from the adjoining ones. Evidently the algae started on what was then the lake bottom. This is also suggested by the fact that at some localities the algal limestones stop abruptly and are covered by a deposit of volcanic agglomerate or volcanic ash which obviously was deposited so rapidly as to smother the colonies. On top of these deposits, which may be several feet thick, another layer of limestone developed later. On the other hand, at localities where the overlying deposit is a shaly ostracod limestone or thinly bedded shales, the top of the algal bed is irregular, some patches of colonies having been able to persist longer than others. In such cases it may usually be observed that the colonies gradually tapered in diameter before they were finally extinguished (Pl. 1, fig. 3; Pl. 2, fig. 1).

The difference in character of the bottom affected the algal growth in several ways. Bottoms covered with silt where sediment was actively

[4] W. H. Bradley: *op. cit.*, p. 205.

deposited stimulated upward growth and gave rise to the lobate or finger-like colonies, while steep, rocky bottoms, not so favorable for the accumulation of sediments, permitted a freer growth of the simpler domal or botryoidal types.

Theoretically, differences in depth with consequent differences in intensity of light could greatly affect the growth of the algae and the type which would grow on the lake bottom. This is considered by many to be the most important factor in regulating the distribution of modern marine algae. In the South Park lakes this probably had an important part in localizing the algal deposits, but as far as can be determined exerted little effect on the character of growth, because they were shallow and therefore adequate light was available everywhere.

CHARACTER OF THE REEF-FORMING ORGANISMS

To determine definitely the character of the lime depositing algae it is necessary to have an idea of their tissues and cellular structure.

Unfortunately, at many localities, the limestones, even though showing some macro-structure, have been so altered by solution, recrystallization, and silicification that all trace of the original cellular structure has been obliterated. However, a study of many collodion peels and thin sections of specimens from all localities where the limestones show good macro-structure yielded some which gave suggestions as to the character of the plant tissues, and a few which indicated cellular structure. The growth, habits, and character of the colonies were observed on many weathered, sawn, or polished specimens and with the aid of collodion peels and thin sections. Inasmuch as all the limestones are similar in appearance and appear to have been deposited under very similar ecological conditions, it is inferred that the types of organisms found to have built some of them were probably responsible for all.

The limestones were built up by arched layers of small, nearly spherical shells of calcite which represent molds of algal cells. The space between may or may not be filled with secondary calcite. In some the material is silicified. These spherical cells are about 16 microns in diameter. They appear to be arranged irregularly in the layers, but this may be due to the angle at which the thin section was cut. In some they are tightly packed; in others they are not. Between the cell layers are irregular spaces filled with coarsely crystalline calcite or more rarely empty.

Just how these delicate cell molds were formed is not definitely known. Obviously, they were formed contemporaneously with the growth of the algae. The idea generally accepted is that there was a precipitation of $CaCO_3$ on the surface of the living plant tissue as a result of photosynthesis, the normal process by which the plant removes CO_2 from water

to take care of its physiological needs. If the water contained calcium bicarbonate in solution the removal of some of the CO_2 would cause a reduction of the CO_2 content of the water, reducing the concentration of the carbonate ion in the system, thereby causing a precipitation of calcium carbonate as a purely chemical process without any further activity of the plant. However, a study of modern lakes where algal limestones are forming shows that with the lime-depositing algae grow other forms, sometimes belonging to the same genera, which do not deposit lime although they certainly use CO_2. This suggests that the process is more complex than that outlined and is probably related to some special form of metabolism in the lime-depositing forms as has been suggested by Pia.[5]

The cells belong to algae which, except for size, were almost identical with *Chlorellopsis coloniata* Reis described by Bradley[6] as the chief builder of algal limestones in the Eocene Green River lakes of western Colorado. However, they are much smaller (only about a seventh as large). Certainly they were a similar type of alga and had similar habits, but by analogy with modern forms they would belong to a different genus.

During life the unicells were probably held together by a gelatinous material. The method of reproduction and color of these forms is not definitely known. However, the spherical shape and small size of the cells indicate forms similar to modern Cyanophyceae. The environmental conditions in the Oligocene lakes of South Park were the same as those under which blue-green algae now thrive, so it is assumed that they belonged to the Cyanophyceae.

DESCRIPTION OF THE ORGANISM

The following classification is proposed:

Class CYANOPHYCEAE

Order COCCOGONEAE

Family CHROOCOCCACEAE

Oncobyrsella gen. nov.

Colonies lens-shaped to spherical or ovoid, attached; the cells in several layers, spherical or somewhat flattened, of moderate size, about 16 microns in diameter; irregular within the colony but tending to a radial arrangement at the periphery, in life presumably held together in a gelatinous mass. Reproduction not known but probably by simple cell division and accidental rupture of colonies. Resembling the modern *Oncobyrsa* in appearance and habit but the cells considerably larger. The name proposed suggests this resemblance, but there is no intention to imply a close relationship.

[5] J. Pia: *Pflanzen als Gesteinbilder* (1928) p. 40, and repeatedly in later papers.
[6] W. F. Bradley: *op. cit.*, p. 207.

Oncobyrsella coloradensis, sp. nov.

(Plate 2, figures 3 and 4)

Colonies usually lens-shaped, from plano-convex to concavo-convex, rarely ovoidal or ob-conical; colonies often united into finger-like masses. Cells spherical or subcuboidal, very uniform at 16 microns diameter. The steep, sometimes overhanging, sides of the colonies suggest that during life the cells were firmly held together in mucilage. In the type specimen the material is preserved by silicification, but in most specimens studied the fossils represent calcite molds and casts of the plants.

Holotype specimen 1205, slides 55 and 66, the author's collection of fossil algae, Colorado School of Mines, Golden, Colorado. Collected by J. Harlan Johnson, July, 1934, SW ¼ S. 1, T. 10 S., R. 75 W., Park County, Colorado, from the lake beds of the Antero formation of Oligocene age.

This species seems to be largely responsible for the algal limestones in the Oligocene lake beds of South Park.

FILAMENTOUS ALGAE

Some thin sections show suggestions of molds of filamentous algae arranged more or less parallel or radially. Other sections show a structure suggesting the molds of a mat or felt of threads massed together without any definite arrangement. Unfortunately, although these several types of filamentous structures are suggested, not enough detail was preserved to permit a worthwhile description. All that can be said is that some thread-like algae lived with the simpler unicellular forms and aided in the lime deposition. Whether they belonged to the blue-green or the green algae cannot be stated. By analogy with modern lakes, it would be expected that either or both would be present.

Colorado School of Mines, Golden, Colo.
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TULLY LIMESTONE AND FAUNA IN PENNSYLVANIA

BY BRADFORD WILLARD

(*With Description of the Cephalopods by A. K. Miller*)

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INTRODUCTION

HISTORICAL SKETCH

The Second Pennsylvania Geological Survey reported "Tully" limestone but listed no characteristic fossils. So far as can be determined, none of their localities shows true Tully. Nevertheless, it is not impossible that that organization may actually have found the Tully, as all of their localities could not be rediscovered. The earliest record of the discovery in Pennsylvania of unquestioned Tully limestone with a diagnostic fossil (*Chonetes aurora*) appears to be that of Butts in 1918.[1] Until 1934, this remained unique. In that year, and subsequently, the writer has reported

[1] Charles Butts: *Geologic section of Blair and Huntingdon counties, central Pennsylvania*, Am. Jour. Sci., 4th ser., vol. 46 (1918) p. 523-537, particularly p. 524-525.

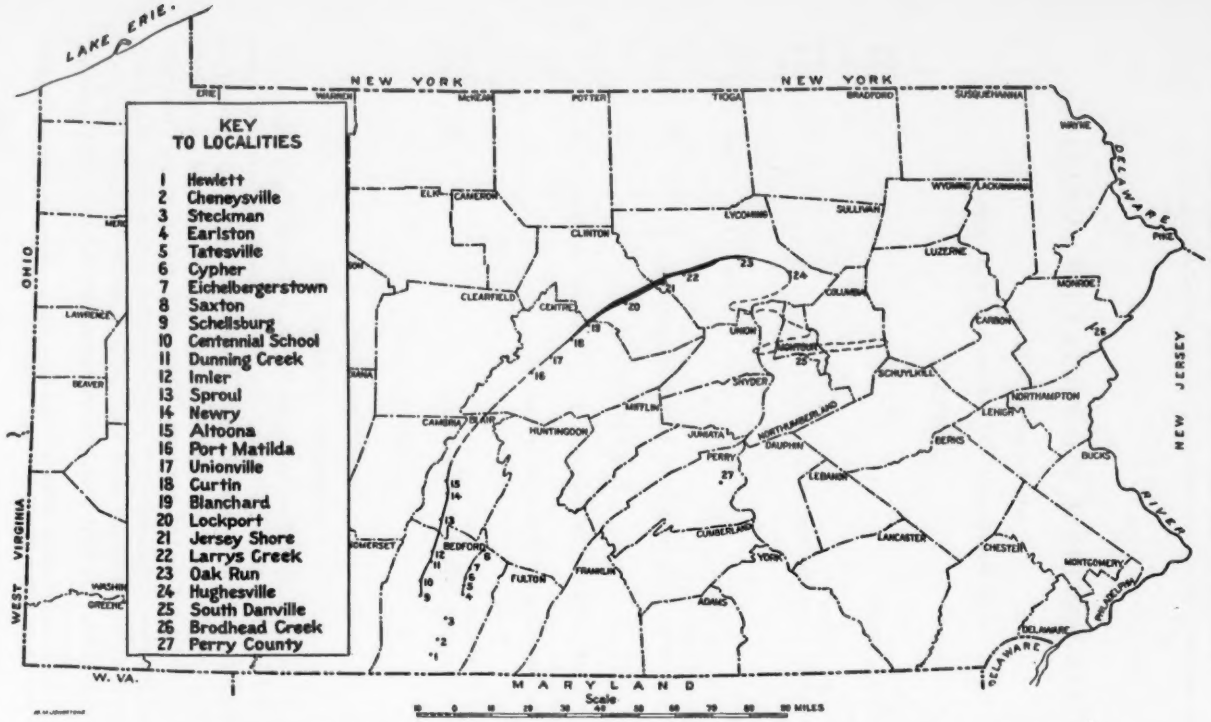

FIGURE 1.—*Sketch map showing distribution of Tully limestone and fauna in Pennsylvania*

Actual exposures of the Tully are known at localities 5, 7, 9, 10, 11, 12, 13, 15, 16, 17, 18, 19, 20, 21, 22, 23, 25, and 27. At 26 is an occurrence of Tully fossils independent of the characteristic lithology. Other numbers indicate some of the more important sections studied, where the Tully is either absent or hidden.

the occurrence of Tully limestone and fossils in the State.[2] These papers give an incomplete description of the Tully, because it had not been possible thoroughly to digest the data on hand at the time when these articles were prepared. The writer purposes now to present a fuller account of the Tully limestone and its fossils in Pennsylvania.

STRATIGRAPHY

GEOLOGIC SEQUENCE

The Tully limestone marks the base of the Upper Devonian over a considerable area in Pennsylvania and serves as a convenient datum to separate it from the Middle Devonian. In central Pennsylvania, where most of the Tully exposures occur, the sequence may be summarized thus:

PORTAGE GROUP

Fort Little formation

Parkhead sandstone
Trimmers Rock sandstone
Braillier shale
Harrell shale

Rush formation

Burket ("Genesee") shale
Tully limestone

MIDDLE DEVONIAN

Mahantango formation [3]

Marcellus formation
Onondaga formation [4]

DISTRIBUTION AND THICKNESS

The Tully limestone exposures in Pennsylvania are principally confined to the central and south-central parts of the State. Most of them are included in the long arc of Devonian formations which follows the base of the Allegheny Front (Fig. 1) between Bedford and Lycoming counties.

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[2] Bradford Willard: *A Tully limestone outcrop in Pennsylvania*, Pa. Acad. Sci., Pr., vol. 8 (1934) p. 57-62; *Hypothyridina venustula (Hall) in Pennsylvania*, Am. Jour. Sci., 5th ser., vol. 29 (1935) p. 93-97; *Portage group in Pennsylvania*, Geol. Soc. Am., Bull., vol. 46 (1935) p. 1195-1218, particularly p. 1209-1212; *Middle-Upper Devonian contact in Pennsylvania*, Pa. Acad. Sci., Pr., vol. 9 (1935) p. 39-44.

[3] Hamilton, *sensu stricto*, divided in east into Moscow, Ludlowville, and Skaneateles formations.

[4] Until 1936 the writer did not include this formation in the Hamilton group. Recent studies of the Onondaga fauna and stratigraphy have suggested such a grouping in Pennsylvania. See: Bradford Willard: *The Onondaga formation in Pennsylvania*, Jour. Geol., vol. 44 (1936) p. 578-603; *Hamilton Correlations*, Am. Jour. Sci., vol. 33, 4th ser. (1937) p. 264-278.

Isolated exposures have been found also in northeastern Bedford County, eastern Perry County,[5] and east-central Northumberland County. A unique example of the fauna exists in the basal Trimmers Rock sandstone in Monroe County (locality 26).

Thickness changes of the Tully in Pennsylvania are its most remarkable feature. In southern Bedford County (localities 1, 2, 3 and 4), neither limestone nor fauna is known. Throughout this region as far as the Maryland line the top of the Hamilton with determinative fossils is succeeded disconformably either by the nearly barren Burket ("Genesee") black shale or by the gray Harrell shale with a Naples fauna. In certain sections the upper part of the Tully is shaly and grades into the Burket. Where no shaly upper Tully was observed, the contact with the Burket is sharper, though probably everywhere transitional. The base may be either limestone or shale, and the Tully seems everywhere to be in disconformable contact with the Hamilton, *sensu stricto.*

At Tatesville (locality 5) along the Huntingdon and Broad Top Railroad, two thin limestones, each a few inches thick, and separated by dark shale, carry *Chonetes aurora* and a few other fossils. These limestones overlie shales of Hamilton age, and are overlain by the Burket. This is the only observed instance in the State of such a split in the limestone—that is, a recurrence of Tully conditions and fauna after an interval of deposition of mud. The Tatesville locality is the southern extremity of a small outlier of the Tully in eastern Bedford County. South from Tatesville in the vicinity of Everett, the Burket black shale rests directly upon the Hamilton, with no indication of limestone between. North of Tatesville, at Eichelbergerstown (locality 7), the Tully is exposed in a road-cut. Here the limestone is 2 feet, 6 inches thick, is overlain by Burket shale, and rests upon Hamilton shale. This occurrence is illustrated in Plate 1, figure 1. The Tully probably does not extend much farther north in this outlier, as it has not been recognized in Huntingdon County, nor is it known farther east at this latitude.

The Tully maintains a fairly uniform thickness north of Schellsburg, being 3 feet thick at Centennial School (locality 10), about the same in Dunning Creek Valley (locality 11), and 4 feet exclusive of perhaps 8 feet of underlying shale above the Hamilton at Imler (locality 12). It thins slightly into Blair County to about 2 feet at Sproul (locality 13), and Butts[6] observed only one foot near Altoona (locality 15). From that point, it increases gradually, with not less than 7 feet exposed near Port Matilda (locality 16), in a cut on the main highway. On the same

[5] In the spring of 1937, three additional occurrences were found in Perry County, all near and similar to that first discovered, which is on the Juniata River above Amity Hall.

[6] Charles Butts: *op. cit.*, p. 524.

FIGURE 1. TULLY LIMESTONE EXPOSED IN ROAD-CUT AT EICHELBERGERSTOWN
White bags show the limestone contacts — Burket shale, right; Hamilton shale, left.

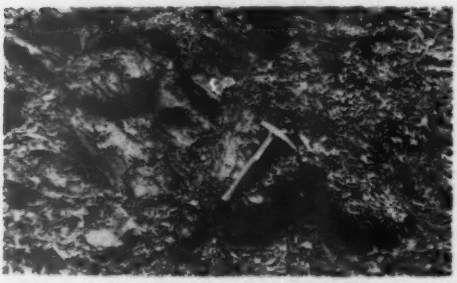

FIGURE 2. BURKET-TULLY-MOSCOW SUCCESSION ON JUNIATA RIVER
Eight miles below Newport. Hammer rests on Tully shale with limestone nodules; Burket shale (right), Moscow shale (left). Note the close lithologic similarity of the three members.

FIGURE 3. DETAIL OF PLATY PHASE OF TULLY LIMESTONE EXPOSED AT LOCKPORT

road, 2 miles east of Unionville (locality 17), it is 30 feet thick; and it reaches 32 feet on Bald Eagle Creek (locality 18) near Curtin, to which may be added 3 to 4 feet of limy shale between the limestone and the Burket. This is one of the best exposures in south-central Pennsylvania. It is estimated to be 30 feet thick in a poor section on the highway at Blanchard (locality 19). Exposures 16, 17, 18, and 19 are along the northwest side of Bald Eagle Creek. For years, these or similar exposures have been mistaken for the Helderberg, which group is confined to the southeast side of the valley and is separated from the Tully by probably not less than 1200 feet of Oriskany and Middle Devonian beds. Incidentally, the Tully of this region, particularly if deeply weathered, may resemble the shaly, local facies of the Onondaga. A few minutes spent in collecting will serve to distinguish the two formations faunally.

Northwest in Clinton and Lycoming counties, a remarkable thickening of the Tully takes place. From some 30 feet at Blanchard, the thickness of the limestone and shale increases to not less than 200 feet at Lockport, across the Susquehanna River from Lock Haven (locality 20; Pl. 1, fig. 3). This is a horizontal distance of only 10 miles. The thickness is maintained eastward for 15 miles. East of Jersey Shore, at the second highway bridge across the Susquehanna River, about 100 feet of Tully crops out along the east bank. It is faulted and folded and represents at most only the upper two-thirds (locality 21). The greatest thickness was discovered along the Susquehanna River, 2 to 3 miles east of Jersey Shore, south of Larrys Creek Station on the New York Central Railroad. Here, two broad, low anticlines bring up the Tully. The greatest measurable thickness, about 250 feet, was found in the southern anticline. Unfortunately, in all these thick sections the base is hidden.

East of Larrys Creek Station, the Tully thins rapidly. On Oak Run (locality 23), there is 5 feet of limestone, with which may properly be included about 50 to 60 feet of overlying, limy shale and 11 feet of underlying shale with limestone nodules. None of these was identified upon paleontological evidence, but the lower shale rests upon the upper Hamilton. At locality 24, west of Hughesville, the only evidence found for the Tully was some residual, reddish clay thought to lie at the base of the Burket. In Northumberland County, at South Danville (locality 25), is 10 feet of Tully limestone and 13 feet of overlying limy shale with Tully fossils. Doubtfully, the writer includes in the Tully 20 to 25 feet of barren, limy shale below this limestone.[7] This is the easternmost known outcrop of the limestone, but an isolated occurrence of Tully

[7] This interpretation is slightly at variance with the view which the author held early in 1934 about this section. It was then the only Tully which he had seen in Pennsylvania. The underlying shale was grouped with the Hamilton. It is now tentatively placed with the Tully, through analogy with sections to the west.

fossils is found in the base of the Trimmers Rock ("Ithaca") sandstone directly above the Hamilton in Monroe County (locality 26). In eastern Perry County, along the Juniata River, 8 miles below Newport (locality 27), about 2 feet of gray shale with hard, limestone nodules carries *Chonetes aurora, Lopolasma tullium,* and other characteristic fossils. This bed rests upon the top of the Moscow shale with *Vitulina* and is overlain by black Burket shale.

The Tully limestone has been known in New York State for nearly a century, and knowledge of its distribution, character, and fauna there have recently been reviewed and amplified by Cooper and Williams.[8] Between the New York and the Pennsylvania outcrops, where the limestone lies deeply buried, subsurface data have been made available by Fettke,[9] who has recognized the Tully in well-logs from Elk County and east in Bradford County. The greatest thickness of the formation reported by him is 129 feet in central Bradford County. This ties in with the exceptional thicknesses the writer found southwestward from that point, in Clinton and Lycoming counties. It is singular that the Tully should be absent only a few miles south of Jersey Shore in near-by Union County, and in Snyder, Mifflin, Dauphin, and southwestern Northumberland counties, but should be found, much thinned, in Perry County (Pl. 1, fig. 2). Thus, the Burket may be in disconformable contact with the uppermost Hamilton. The line of outcrop (Fig. 1) is essentially the eastern and southern limit of the Tully limestone regardless of thickness.

FACIES

The Tully limestone in Pennsylvania does not appear to be divisible into a succession of stratigraphic units as it is in New York.[10] On the contrary, it is best treated as consisting of two lithologically and faunally distinct but essentially contemporaneous phases or facies. These are exposed respectively in central and south-central Pennsylvania. For convenience, these limestones may be distinguished by the adjectives platy and massive, respectively.

The platy facies is characteristic of the thicker, northern sections and is well developed at Larrys Creek (locality 22), Jersey Shore (locality 21), and Lockport (locality 20). Also, it is known in the thinner sections east to South Danville (locality 25) and south to Curtin (locality 18). It is a light-gray, non-crystalline limestone in beds averaging about 2 inches in thickness (Pl. 1, fig. 3), and usually separated by thin partings of black shale. The base has been seen in few sections, but appar-

[8] G. Arthur Cooper and J. Stewart Williams: *Tully formation of New York,* Geol. Soc. Am., Bull., vol. 46 (1935) p. 781-868.

[9] Charles R. Fettke: *Subsurface Devonian and Silurian sections across northern Pennsylvania and southern New York,* Geol. Soc. Am., Bull., vol. 44 (1933) p. 601-660.

[10] G. Arthur Cooper and J. Stewart Williams: *op. cit.,* p. 788-792.

ently it passes over into limy shale, which, in turn, rests disconformably upon the Hamilton. An upward change is noted in the top of most sections that grade through limy shale into the black, Burket member. The platy limestone weathers light-gray to brownish gray. When struck with the hammer, a fresh specimen is usually slightly fetid. Fossils are rather rare, except in the upper part of the limestone and the succeeding limy shale.

The massive facies of the Tully limestone is confined to Bedford, Blair, and southern Centre counties. It in itself varies. Everywhere quite unlike the northern, platy type, it consists principally of massive, dense, dark-gray to dove-colored, hard, fine-grained limestone, which breaks with a conchoidal or sub-conchoidal fracture. In places it contains small calcite crystals scattered through the mass in such a way as to give a spangled appearance to fracture surfaces. This limestone yields "nigger-heads," plowshare-shaped or hour-glass-shaped residual boulders. Scattered over the surface, these may be the only evidence of the presence of the Tully. In many places the weathered surface is buff or light-brown and clayey. Commonly, though not invariably, it has a fetid odor when hammered. Associated with this phase is another minor variation. This is hard, crystalline, dark gray, rather fine-grained limestone, in beds at least 2 inches thick. The weathered surface may appear pitted and is usually light-brown. It, too, may be fetid when freshly broken.

The massive phase of the Tully is more fossiliferous than the platy phase. The faunas of the two phases are as distinctive as their lithologies. Corals, including *Lopholasma*, are mostly found in the northern type, rarely in the southern. *Elytha fimbriata* appears to be confined to the platy facies, as, too, are most of the species of *Spirifer*, a sprinkling of mollusks, and some trilobites. In its upper part, *Atrypa spinosa* is commonly abundant, associated with *Phacops rana*. The massive facies, on the other hand, carries exclusively a large species of *Emanuella* (herein first described) and great numbers of *Chonetes aurora*, a brachiopod almost unknown in the north. This last is commonly associated with *Echinocoelia ambocoelioides* and *Hypothyridina*, forms rare but not entirely unrecognized in the platy limestone. For a complete comparison of the faunas of the two facies and for all important localities, Table 1 may be consulted.

It must not be supposed that there is any hard and fast line of geographic or stratigraphic separation between the two types of Tully limestone in Pennsylvania. Were that the case, the writer would be inclined to consider them non-contemporaneous and make direct correlation with the New York Tully subdivisions. On the contrary, the facies intergrade laterally. The section at Curtin (locality 18) illustrates this admirably.

Here, platy limestone like that at Lockport or Larrys Creek carries interbeds, 6 inches to a foot thick, whose lithology is that of the massive facies to the south. At both Curtin and Lockport, a shaly upper portion is transitional into the Burket, and a zone replete with *Atrypa spinosa* and *Phacops rana* is a prominent feature of the upper part. As the tops of these sections are clearly contemporaneous, and the Curtin section is so much thinner than the Lockport one, it is probable that the massive limestone of the south equals only the upper portion of the platy northern sections. Conversely, the lower part of the thick northern sections is probably older than any of the Tully farther south. As support to the idea of lithologic transition at Curtin, one should observe that *Emanuella pennsylvanica* was found here with *Echinocoelia ambocoelioides* and a single fragment of *Hypothyridina,* but that *Chonetes aurora* was not collected at this exposure. The Perry County faunules ally themselves with the southern facies.

CORRELATION

The writer found it impracticable to subdivide the Tully in Pennsylvania as has been done in New York. Nevertheless, there are interesting comparisons between the two areas. Cooper and Williams[11] give the following divisions in New York: West Brook member [upper]; Apulia member [middle]; Tinkers Falls member [lower].

In lithology and fauna the platy facies in the north most nearly approximates the West Brook member of the New York succession, but it also resembles the Tinkers Falls. Yet it carries an occasional *Hypothyridina,* unknown in the Tinkers Falls; and *Echinocoelia,* an Apulia fossil, has been found, though rarely, in several sections. The southern, massive facies suggests the Apulia member with heavier beds containing *Hypothyridina* and an abundance of *Chonetes aurora.* The only specimen of *Charinoella* found in Pennsylvania Tully was taken from this facies, whereas this genus is found only in the West Brook member in New York. Judging from the conflicting data, the writer is inclined to look upon the Pennsylvania Tully, as a whole, as more or less equivalent to the upper part of the New York formation. It combines lithology and fossils that, to the north, are characteristic of chronologically distinct members. In Pennsylvania, these are found, if not together at the same locality, at least in contemporaneous, laterally intergradational phases. Apparently, the Tinkers Falls is absent. The Perry County occurrences suggest West Brook.

A passing remark is pertinent regarding the Tully fossils from locality 26 on Broadhead Creek, Monroe County, which the author has already

[11] *Op. cit.*, p. 790, see also their list of Tully fossils, p. 855-859.

described.[12] This faunule from the base of the Trimmers Rock ("Ithaca") sandstone is given in the faunal table for the entire Tully. The writer has suggested its equivalence, on the basis of lithology, stratigraphic position, and geographic location, to the Laurens member of "eastern" New York. Comparison shows that, of the fossils specifically identified here, *Liorhynchus mesacostale, Hypothyridina venustula,* and *Echinocoelia ambocoelioides* occur in the Laurens.

ORIGIN

The rapid changes of thickness, the lithologic differences, and the abrupt cessation (except for Perry County) of the Tully east and southeast of the line of outcrop in Pennsylvania suggest unusual conditions, perhaps associated with lagoons and barrier reefs. Unfortunately, for this theory, there is a relative scarcity of corals and other reef-building organisms. The disconformity with the Hamilton is significant.[13] Nowhere has a Hamilton-Tully transition been identified. In most sections in eastern and central Pennsylvania, the top of the Hamilton carries *Vitulina pustulosa,* as in New York. In south-central Pennsylvania, where this is lacking, the faunal evidence points to the absence of the equivalent of perhaps all of the highest Hamilton formation, the Moscow. Yet, no angular difference of dips between the Tully and the Hamilton has been measured. Therefore, it is inferred that the break is non-depositional rather than diastrophic. At the same time, it has been shown that the basal Burket is, from its fauna and its relations to overlying Portage units, essentially synchronous across central Pennsylvania. The Tully pinches out southward, and, beyond its limits in southern Bedford County, the Burket does likewise, so that the Harrell eventually comes to rest directly upon the Hamilton. This implies on-lap toward the south or southeast during and following Tully time. Presumably after the off-lap, near the commencement of Moscow time, there was a diastem of non-deposition whose duration was progressively shorter northward. The Tully sea encroached upon this region. As yet undiscovered, off-shore, coastal reefs may have developed. Transgression was slow. The lower portions of the thicker sections to the north, in Clinton and Lycoming counties (and presumably, judging from well records, as far northeast as Bradford County at least), may have been formed before any Tully was laid down to the south. Thus, only the highest beds in the thick sections are perhaps the equal of the entire Tully of the thinner sections to the south (or east). The writer has for some time held the belief that

[12] Bradford Willard: *Portage group in Pennsylvania,* Geol. Soc. Am., Bull., vol. 46 (1935) p. 1218. Since this paper was printed, additional fossils have been collected (summer 1935) and are incorporated in the faunal list to follow.

[13] Bradford Willard: *op. cit.,* p. 1195-1196; *Middle-Upper Devonian contact in Pennsylvania,* Pa. Acad. Sci., Pr., vol. 9 (1935) p. 39-44.

during the Paleozoic era, the region of south-central Pennsylvania was one of crustal instability. Such an hypothesis is borne out here if the significance of the hiatus between the Middle and the Upper Devonian in south-central Pennsylvania is correctly evaluated.

The Tully fauna may have succeeded in penetrating far east of the region of characteristic calcareous lithology. Such an extension would account for the Monroe County occurrence. On the other hand, that faunule may have arrived directly by an independent route or connection with "eastern" New York. Its similarity to the Laurens makes such a supposition the more probable, especially as no Tully fossils have been found between Northumberland and Monroe counties.

SUMMARY AND CONCLUSIONS

The writer has described the distribution and thickness of the exposed Tully in Pennsylvania, its lithology and variations and its faunal aspect. The Tully does not lend itself to subdivisions, as in New York, but is resolved, north and south, into two contemporaneous facies of lithologic dissimilarity but laterally transitional. Comparatively few new fossils are recognized, but the known ones tie in closely with New York. These fossils represent the southernmost Tully recognized east of the Appalachians.

DESCRIPTION OF SPECIES

The Tully fauna of Pennsylvania consists almost entirely of previously described species which have been found in the same formation in New York. However, there are a few new species; and, as none of the fossils from the Tully in Pennsylvania, except *Hypothyridina*, has been figured,[14] it is deemed worth while to illustrate several of the more important species, especially such forms as are distinctive of the formation or have not previously been recognized from it here.

Several cephalopods were collected. These were submitted to Professor A. K. Miller, of the University of Iowa, who very kindly examined and described them, and who supplied four figures of *Baeopleuroceras incipiens*. The descriptions are given on a subsequent page. The writer wishes to express his appreciation to Professor Miller for the time and labor he has put upon this material and for the report he has furnished upon this interesting element of the fauna. To Doctor G. Arthur Cooper, of the United States National Museum, the writer is equally indebted. Doctor Cooper has several times examined Tully material collected by the writer in Pennsylvania, and finally has gone over a complete series of the brachiopods, passed upon their identifications, corrected errors, and made valued suggestions.

[14] Bradford Willard: *Hypothyridina venustula (Hall) in Pennsylvania*, Am. Jour. Sci., 5th ser., vol. 29 (1935) p. 93-97.

TABLE 1.—*Fossil list and localities*

Fossil	Schellsburg	Centennial School	Dunning Creek	Imler, shale	Imler, limestone	Eichelbergerstown	Tatesville, ls. on rd.	Tatesville, sh. on rd.	Tatesville, R. R. 180'	Tatesville, R. R. 240'	Sproul	Unionville	Curtin	Lockport	Jersey Shore	Larrys Creek	S. Danville shale	S. Danville limestone	Brodheads Creek	Perry County
Enterolasma rectum (Hall)																	x	x		
E. sp.														x						
Zaphrentis sp.							x													
Amplexus hamiltoniae Hall													x	x	x	x	x	x		
Lopholasma tullium J. S. Williams							x						x	x	x	x		?		x
L. sp.														x						
Aulacophyllum sulcatum d'Orbigny				x																
Aulopora sp.																	x			
Ceratopora dichotoma Grabau																x				
C. sp.														x						
Favosites sp.				x																
Pleurodictyum sp.																		x		
Corals, undet.																	x	x		
Taonurus sp.													x							
"Crinoidea," columnals	x		x	x	x	x	x		x		x	x	x	x	x	x	x	x	x	x
Fenestella sp.									x			x		x	x				x	
Stictopora sp.											x									
Bryozoa, undet.																		x	x	x
Lingula ligea Hall																		x		
Pholidops sp.																	x			
Strophеodonta demissa (Conrad)									x				x							
S. sp.																		x		
Leptostrophia perplana (Conrad)	x															x				
L. sp.										x		x		x		x		x		x
Douvillina sp.											x			x						
Leptaena rhomboidalis (Wilckens)																x				
Schuchertella variabilis Prosser																		x		
Chonetes aurora (Hall)	x	x		x	x			x	x	x	x	x				x				x
C. lepidus Hall								x			x									
C. coronatus (Conrad)											x									
Productella spinulicosta Hall													x		x	x				
Dalmanella sp.																			x	
Rhipidomella vanuxemi (Hall)																			x	
R. sp.	x							x												
Camarotoechia orbicularis (Hall)														x					x	
C. eximia (Hall)																			x	
Liorhynchus mesacostale (Hall)																			x	
L. globuliforme (Vanuxem)																			x	
L. sp. (cf. *limitare*)														x						
L. sp.	x																			
Hypothyridina venustula (Hall)	x	x	x			x					x		x					x	x	
Pentamerella sp.				x																
Tropidoleptus carinatus (Conrad)									x							x	x		x	?
Atrypa spinosa Hall										x			x	x	x	x		x		x
Spirifer mesastrialis Hall																	x	x		
S. mucronatus (Conrad)								x			x			x	x		x			
S. m. var. *posterus* Hall and Clarke																			x	

TABLE 1.—*Fossil list and localities*—Continued

Fossil	Schellsburg	Centennial School	Dunning Creek	Imler, shale	Imler, limestone	Eichelbergerstown	Tatesville, ls. on rd.	Tatesville, sh. on rd.	Tatesville, R. R. 180'	Tatesville, R. R. 240'	Sproul	Unionville	Curtin	Lockport	Jersey Shore	Larrys Creek	S. Danville shale	S. Danville limestone	Brodheads Creek	Perry County
S. tullius Hall									x		x		x	x		x				
S. pauliformis J. S. Williams																		x		
S. sp.														x					x	x
Elytha fimbriata (Conrad)													x		x	x		x		x
Ambocoelia umbonata (Conrad)													x			x		x		
Echinocoelia ambocoelioides Cooper and Williams	x	x	x	x	x	x		x		x	x	x	x	x		x	x	x	x	x
Cyrtina sp.				x											x			x		
Charionella ovata (?) J. S. Williams													x							
Emanuella pennsylvanica Willard sp. nov.																				
Coelopsira ?													x							
"*Martinia*" sp.	x	x	x	x						x	x		x							x
Athyris sp.																			x	
Grammysia arcuata (Conrad)								x												
Buchiola susquehannica Willard sp. nov.																x				
Nucula corbuliformis Hall																	x			
Palaeoneilo sp.														x						
Leptodesma sp.													x							
Actinopteria boydi (Conrad)														x						
Cypricardella sp.																x				
Paracyclas sp.																	x			
Pleurotomaria capillaria Conrad											x									
P. sp.														x		x	x			
Euomphalus sp.													x							
Loxonema hamiltoniae Hall													x							
Platyceras carinatum Hall															x					
Styliolina fissurella (Hall)								x				x		x		x		x		
Tentaculites desciscus Clarke and Swartz	x																			
T. bellulus (Hall)																	x			
Hyolithes sp.																x				
"*Orthoceras*" sp. 1													x							
Spyroceras nuntium (Hall)													x					x		
Baeopleuroceras incipiens J. S. Williams													x							
Probeloceras lutheri Clarke																x				
Bactrites sp.									x											
Phacops rana (Green)											x	x	x	x	x					x
P. sp.							x								x	x		x		
Proëtus rowi Green														x						
Greenops (Dalmanites) boothi (Green)															x		x			
G. b. var. *callitelos* (Hall and Clarke)													x		x					x
G. bedfordensis Willard, sp. nov.	x			x																
G. sp.														x		x				
Ostracoda, undet.												x				x				
"Ostracoderm" plate, undet.															x					
Plant fragments, woody													x						x	
Fucoids													x				x			

ANTHOZOA

TETRACORALLA

Lopholasma tullium J. S. Williams

(Plate 2, figures 16, 28)

G. Arthur Cooper and J. Stewart Williams, Geol. Soc. Am., Bull., vol. 46 (1935) p. 837-838. Pl. 58, figs. 1, 2, 5, 9.

DIMENSIONS: Length 16 mm., width at top 8 mm.

REMARKS: All specimens from Pennsylvania are somewhat smaller than those described by Williams, but are otherwise quite similar.

OCCURRENCE: This species is fairly common in the shaly upper beds of the Tully in the thick, northern sections of the platy phase of the limestone, particularly at Lockport, Jersey Shore, and Larrys Creek. It is doubtfully identified from South Danville and was found sparingly at Tatesville. The latter is the only record of its appearance in the massive Tully of the southern sections.

BRACHIOPODA

Douvillina sp.

REMARKS: This genus is represented from the Tully by only a few fragmentary specimens, showing the depressed convex form and the characteristic alternation of striae.

OCCURRENCE: This brachiopod occurs in both platy and massive Tully limestone in Pennsylvania. It is recorded from Tatesville, Unionville, Lockport, Larrys Creek, and South Danville. The single specimen from Larrys Creek was taken from the limy shale above the limestone. It is nowhere common.

Chonetes aurora (Hall)

(Plate 2, figures 6, 11)

Small plano-convex shell of sub-quadrangular to semi-circular outline. Hinge-line straight; extremities rounded and flattened. Six spines present along posterior margin. Anterior margin straight or slightly undulatory. Ventral valve gently rounded without sinus or fold, flattened in cardinal extremities. Dorsal valve usually flat or slightly concave. Surface marked by low, rounded plications increasing by bifurcation and implantation to between 30 and 40 along anterior margin in large individuals and dying out at cardinal extremities. Plications crossed by numerous concentric lines which give the surface its distinct and attractive pattern. The interior of the ventral valve carries a short median septum and flabellate muscle scars which, in internal casts, yield a prominent raised area. Dorsal interiors not preserved in this material.

DIMENSIONS: Length 5½ mm., width 6 to 7 mm. Greatest width about 1½ mm. anterior to hinge-line.

OCCURRENCE: This species is nearly restricted to the southern phase of the Tully, where it is abundant in many places, as in the limestone on the railroad at Tatesville, at Unionville, and other places. It was found in the north only at Larrys Creek, but is abundant in Perry County.

Hypothyridina venustula (Hall)

(Plate 2, figures 17, 18, 20, 21, 22)

This is readily recognized by its cuboidal outline and strong plications. The ventral valve is convex, shallow, and has a small beak and broad shallow sinus. The valve turns sharply up anteriorly in a high, broad vertical lobe. Dorsal valve very gibbous in mature, more depressed in younger, individuals and with a broad, low median fold. The fold and sinus usually carry five to eight strong plications, and the lateral areas may have as many as twenty each. Internal casts of the ventral valve show a strong muscle scar and ovarian sinuses. The margin of many specimens bears a row of deep pits.

DIMENSIONS: A large individual measures, length 20 mm., width 24 mm., height 13 mm.

REMARKS: There are some slight variations in form in this brachiopod, but none of importance. Individuals found in the southern facies are usually plumper than those in the north or in the "Laurens".

OCCURRENCE: This brachiopod is one of the few fossils found in both phases of the Tully. It is more abundant in the south, though never common. A single fragment was found at Curtin, which locality is transitional between the two phases, and two specimens have been taken from the limestone at South Danville[15] and several from the "Laurens" in Monroe County. None was found in Perry County.

Pentamerella sp. undet.

(Plate 2, figure 29)

A single, fragmentary, ventral valve of what appears to be a *Pentamerella* was collected from the Tully in Pennsylvania. It is in many respects near *P. dubia*, but too little is known of this fossil to allow closer identification. It shows a prominent, curved umbo and is moderately ventricose. The surface is marked by about sixteen strong plications which are rounded posteriorly but grow flatter anteriorly. Concentric growth lines are present.

DIMENSIONS: Length 14 mm., width 12 mm.

OCCURRENCE: Tully shale underneath the massive limestone at Imler.

Spirifer mesastrialis Hall

This large spirifer is characterized by its coarse lateral ribs and by having the fold and sinus marked, in well-preserved examples, by fine radiating lines. The form varies somewhat from specimens with a wide hinge-line to plump individuals. The lateral slopes carry about fifteen rather broadly rounded plications. Concentric lines of growth are inconspicuous or lacking.

DIMENSIONS: A large specimen measured, length 28 mm., width 54 mm.

OCCURRENCE: This fossil was found only at South Danville, where it is seen in both the limestone and the shale in some places, but more commonly in the latter.

Spirifer pauliformis J. S. Williams

(Plate 2, figures 8, 9)

G. Arthur Cooper and J. Stewart Williams, Geol. Soc. Am., Bull., vol. 46 (1935) p. 842-843, pl. 59, figs. 3, 4, 5, 29.

DIMENSIONS: Length 6 mm., width 11 mm.

REMARKS: Two examples of this species were found representing external molds of the dorsal valve. Although both are small, they fit Williams's description closely.

OCCURRENCE: Platy Tully limestone at South Danville.

[15] Bradford Willard: *op. cit.*

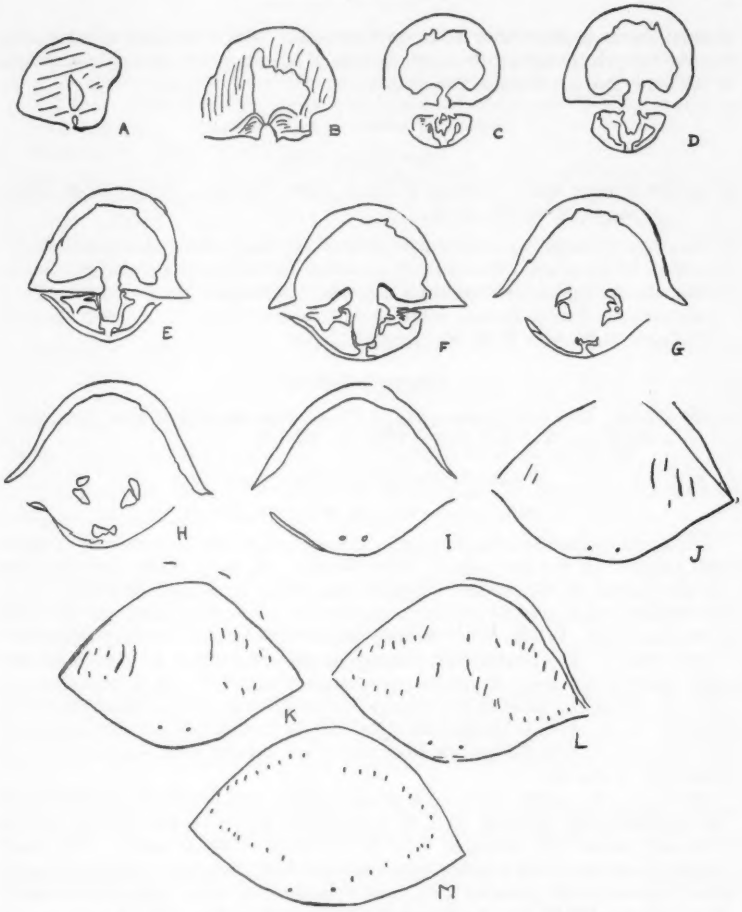

FIGURE 2. *Transverse sections of Emanuella pennsylvanica.*

Prepared by G. Arthur Cooper. Section A is 2.5 mm. from beak, B is 3.75 mm., C 4.5 mm., D 4.6 mm., E 5.3 mm., F 5.5 mm., G 6 mm., H 6.5 mm., I 7 mm., J 8.5 mm., K 9 mm., L 10 mm., M 12.5 mm.

Echinocoelia ambocoelioides Cooper and Williams

(Plate 2, figures 1, 2, 3)

G. Arthur Cooper and J. Stewart Williams, Geol. Soc. Am., Bull., vol. 46 (1935) p. 844-845, pl. 59, figs. 9, 13, 17, 21, 23, and text figure 5.

DIMENSIONS: Length 14 mm., width 13 mm.

OCCURRENCE: This brachiopod is the most widely distributed of all the Tully fossils in Pennsylvania. It was found at practically every locality, but is far more

abundant in the southern than in the northern phase. This, or a closely allied species, has also been recognized by the writer in beds of late Hamilton age, and occurs also in the lower Portage shales of Pennsylvania.

Charionella ovata? J. S. Williams

(Plate 2, figures 4, 5)

G. Arthur Cooper and J. Stewart Williams, Geol. Soc. Am., Bull., vol. 46 (1935) p. 843, pl. 59, figs. 18, 22, 26.

The single specimen is a crushed individual which clearly shows the typical internal characters of the genus. The external characters fit Williams's description. Nevertheless, the limited material prevents a precise identification.

DIMENSIONS: Length 15 mm., width 13 mm., height 8 mm.

OCCURRENCE: Massive Tully limestone at Curtin.

Emanuella Grabau

A. W. Grabau, Devonian Brachiopoda of China, Palaeontologia Sinica, Geol. Surv. China, ser. B., vol. 8, fasc. 3 (1931) p. 409-410.

Emanuella pennsylvanica Willard, *sp. nov.*

(Plate 2, figures 10, 25, 26, 27 and text figure 2)

The genus *Emanuella* is represented in Pennsylvania Tully by numerous examples here assigned to the new species *pennsylvanica*. It most nearly resembles the Chinese species *E. takwanensis* (Kayser), but differs in several particulars. It is considerably larger, and the general proportions of the shell are different. The shell is medium-sized. Pedicle valve strongly and evenly convex; brachial valve moderately convex. The length-width proportions are about equal, in both young and adult individuals. Beak of pedicle valve strongly incurved over a triangular delthyrium. Hinge line two-thirds as long as greatest width of shell; cardinal extremities rounded. Some old individuals show slight trace of median fold and sinus anteriorly. Surface smooth save for growth lines which are usually faint but may become prominent in old age.

Internally, the pedicle valve lacks dental laminae but has strong cardinal teeth. The brachial valve is much as in *E. takwanensis*, with two well-marked brackets extending inward and diverging from their closely proximal bases. These reach anteriorly and are nearly parallel, though in some shells they show slight convergence. Deep sockets in their posterior parts receive the cardinal teeth. The species suggests *E. subumbona* (Hall), but it is larger, the beak of the pedicle valve is more curved, and the hinge line is shorter.

DIMENSIONS: Type specimen: Length 21 mm., width 22 mm., height 14 mm., length of hinge line 14 mm.

OCCURRENCE: Abundant in the southern, massive Tully in Pennsylvania.

PELECYPODA

Buchiola susquehannica Willard, *sp. nov.*

(Plate 2, figure 7)

This species most nearly resembles *B. retrostriata* (von Buch), which is common in the succeeding Burket ("Genesee") black shale in Pennsylvania, but it is distinguished by its few plications and by other external ornamentation. The surface

is marked by seven prominent, rounded costae which are sharply separated from the intervening furrows. The furrow or space between each pair of ribs is broken by seven or eight prominent, transverse nodes which are themselves crossed by two concentric lines. Toward the anterior margin the ribs are smaller and the nodes disappear. Interior unknown.

DIMENSIONS: Height 6 mm., length 7 mm.

REMARKS: The species is based upon a single, well-preserved mold of the left valve. It is noteworthy that this genus is common in the overlying Burket but is rare in the Tully of Pennsylvania. This, and the occurrence with it of a cephalopod close to, if not identical with, *Probeloceras lutheri*, a Naples form, serve to tie in the Tully with the overlying Portage shales.

OCCURRENCE: Tully shale above the platy limestone in the northern anticline at Larrys Creek.

GASTROPODA

Pleurotomaria capillaria Conrad

(Plate 2, figure 15)

James Hall, N. Y. Geol. Surv., vol. 5, pt. 2 (1879) p. 77-78, pl. 20, fig. 20.

OCCURRENCE: A single small individual was collected at Sproul in the southern phase of the Tully.

ARTHROPODA

TRILOBITA

Greenops bedfordensis Willard, *sp. nov.*

(Plate 2, figures 23, 24)

This trilobite is known only from two pygidia. It resembles most closely *G. boothi* in the form of the eleven marginal spines of the pygidium. But it differs from that species in that these spines are thicker and more pustulose and terminate distally in rounded or bulbous, club-shaped ends rather than in the elongated cylindrical, flattened points of *G. boothi*.

OCCURRENCE: This species appears to be confined to the massive southern phase of the Tully, having been collected at New Buena Vista (Schellsburg) and Imler only.

CEPHALOPODS OF THE TULLY FORMATION IN CENTRAL PENNSYLVANIA

(Plate 2, figures 12, 13, 14, 19)

Bradford Willard has courteously offered the opportunity of studying the cephalopods which he collected from the Tully formation (basal Upper Devonian) in central Pennsylvania. Although the majority of these specimens are not well preserved, some of them are much above average, and considerable information can be gleaned from them.

The ammonoids are not so numerous nor so well preserved as the nautiloids, and, therefore, will be considered first. The collection contains two small straight specimens, from the Tatesville Railroad section in Bedford County (locality 5), which do not retain their sutures but which probably represent the genus *Bactrites*. Forms of this general type have

commonly been referred to *Bactrites? aciculum* (Hall), but little information is available in regard to the cotypes of that species, and the specific affinities of the Tully specimens under consideration are uncertain—they may even be nautiloids or pteropods. One specimen from Lockport in Clinton County (locality 20) superficially resembles *Tornoceras* (*Tornoceras*) *uniangulare* (Conrad), but it is so poorly preserved that its identity as a fossil is not certain. Also, from the northern anticline on Larrys Creek in Lycoming County (locality 22), there is an ammonoid which, though crushed and poorly preserved, is probably referable to *Probeloceras lutheri* (Clark)—that species has been found at many localities and horizons in the "Genesee" and the Naples formation (and equivalent beds) in New York, Pennsylvania, West Virginia, Virginia, and Maryland, but, insofar as I am aware, it has not been reported previously from the Tully.

The nautiloid genus *Spyroceras* is represented, in the collection studied, by three specimens, one from South Danville in Northumberland County (locality 25) and two from a point near Curtin in Centre County (locality 18). Though only two of these retain the surface markings of the test, all of them appear to be conspecific, and they seem to be referable to *S. nuntium* (Hall). That species was originally described from the Hamilton of New York, but it has since been identified from the Marcellus and the Tully of the same State, the Hamilton of Pennsylvania, the Romney of West Virginia and Maryland, the Columbus of central Ohio, the Traverse of northwestern Ohio, and the Onondaga and the Alpena of the Ontario Peninsula. Associated with the representatives of *Spyroceras* from near Curtin are two rather small fragmentary smooth internal molds of orthoconic cephalopods which I am referring to *"Orthoceras"* sp. l. One of these represents only the adapical portion of the living chamber, whereas the other represents part of three chambers of the phragmacone. Neither retains its siphuncle, and, therefore, I am not able to ascertain the precise generic affinities of either of them, nor can I tell whether or not they are conspecific.

Another specimen from the same locality—that is, from the vicinity of Curtin in Centre County—is by far the most significant cephalopod in the collection. It is a representative of the unique species for which Williams[16] recently established the genus *Baeopleuroceras*. All the specimens on which this genus was based are conspecific, being referred to *B. incipiens* Williams, and all came from the West Brook member (*fimbriata* zone) of the Tully at three localities in New York. The occurrence of this same peculiar species in central Pennsylvania seems

[16] J. Stewart Williams *in* G. Arthur Cooper and J. S. Williams: *Tully formation of New York*, Geol. Soc. Am., Bull., vol. 46 (1935) p. 851-852, pl. 60, figs. 24, 27.

significant, and it strongly supports Willard's correlation of the beds in which it is to be found with the Tully limestone of New York and indicates that they are upper Tully (West Brook) equivalents.

The rest of the cephalopods obtained from the Tully in Pennsylvania are, to say the least, compatible with a correlation with the West Brook, for some of them are conspecific with forms known from that member, and, in New York, no cephalopods have been found in the lower and the middle portions (Tinkers Falls and Apulia members) of the Tully. Furthermore, the Pennsylvania representative of *Baeopleuroceras* retains an internal mold of the adorsal three camerae of the phragmacone, and this reveals the nature of the sutures, the septa, and the siphuncle, which previously have not been known in this genus. The camerae are moderately long, and their length (measured along the lateral side of the conch) is equal to about one-fifth their width. The sutures are straight, and they are essentially simple circles—they are not parallel to the lateral plications of the conch but cut across them obliquely. The septa are moderately convex saucer-shaped disks, and they, like the sutures, are directly transverse to the long axis of the conch. The siphuncle is small, and, though subcentral in position, is considerably nearer the dorsum than the venter—its diameter is equal to only about one-eleventh the width of the conch. The septal necks are short and straight, being only about one-fifth as long as the camerae, and the connecting rings, though not preserved in this specimen, apparently were cylindrical.

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DESCRIPTION OF PLATE

PLATE 2. FOSSILS FROM THE TULLY OF PENNSYLVANIA

Echinocoelia ambocoelioides Cooper and Williams

FIGURES 1, 2, 3. Figure 1, ventral; figure 2, dorsal view, showing surface ornamentation, × 1. Figure 3, lateral view, × 1. Specimens from massive Tully of Dunning Creek valley, south-central Pennsylvania.

Charionella ovata? J. S. Williams

FIGURES 4, 5. Dorsal and lateral views, × 1. Specimens from massive Tully limestone at Curtin.

Chonetes aurora (Hall)

FIGURES 6, 11. Figure 11 illustrates surface ornamentation, × 6. Figure 6 is cast of interior of ventral valve, × 3. Specimen 11 from massive Tully limestone of Blair County; specimen 6, massive Tully limestone of Bedford County.

Buchiola susquehannica Willard, sp. nov.

FIGURE 7. Wax replica of left valve of unique specimen, × 2, from shale in highest Tully on Larrys Creek. (Holotype U. S. N. M. 91829.)

Spirifer pauliformis J. S. Williams

FIGURES 8, 9. Two partially crushed, dorsal valves, × 2; both from the shaly Tully limestone at South Danville.

Emanuella pennsylvanica Willard, sp. nov.

FIGURES 10, 25, 26, 27. Dorsal, ventral, posterior, and lateral views respectively, × 2. Figure 27 is partly exfoliated showing interior markings. Figure 10 shows structure of delthyrium. Specimen from massive Tully limestone of south-central Pennsylvania. (Holotype U. S. N. M. 92991A.)

Baeopleuroceras incipiens J. S. Williams

FIGURES 12, 13, 14, 19. Lateral, ventral, and septal views and diagrammatic dorso-ventral, longitudinal section of phragmacone respectively of unique specimen, all × 2. Specimen from massive Tully limestone at Curtin.

Pleurotomaria capillaria Conrad

FIGURE 15. Wax replica of unique specimen, × 4, from massive Tully limestone at Sproul.

Lopholasma tullium J. S. Williams

FIGURES 16, 28. Figure 16, oblique section, × 2. Figure 28, partly exfoliated specimen, × 1. Specimens from shaly, upper Tully on Larrys Creek.

Hypothyridina venustula (Hall)

FIGURES 17, 18, 20, 21, 22. Figures 21, 22, 20 respectively, are dorsal, ventral, and anterior views, × 2. Figure 17 is ventral view, × 1; figure 18 is mold of interior of ventral valve, × 1. Figures 20, 21, and 22 from massive Tully limestone of south-central Pennsylvania; figures 17 and 18 from "Laurens" of Monroe County.

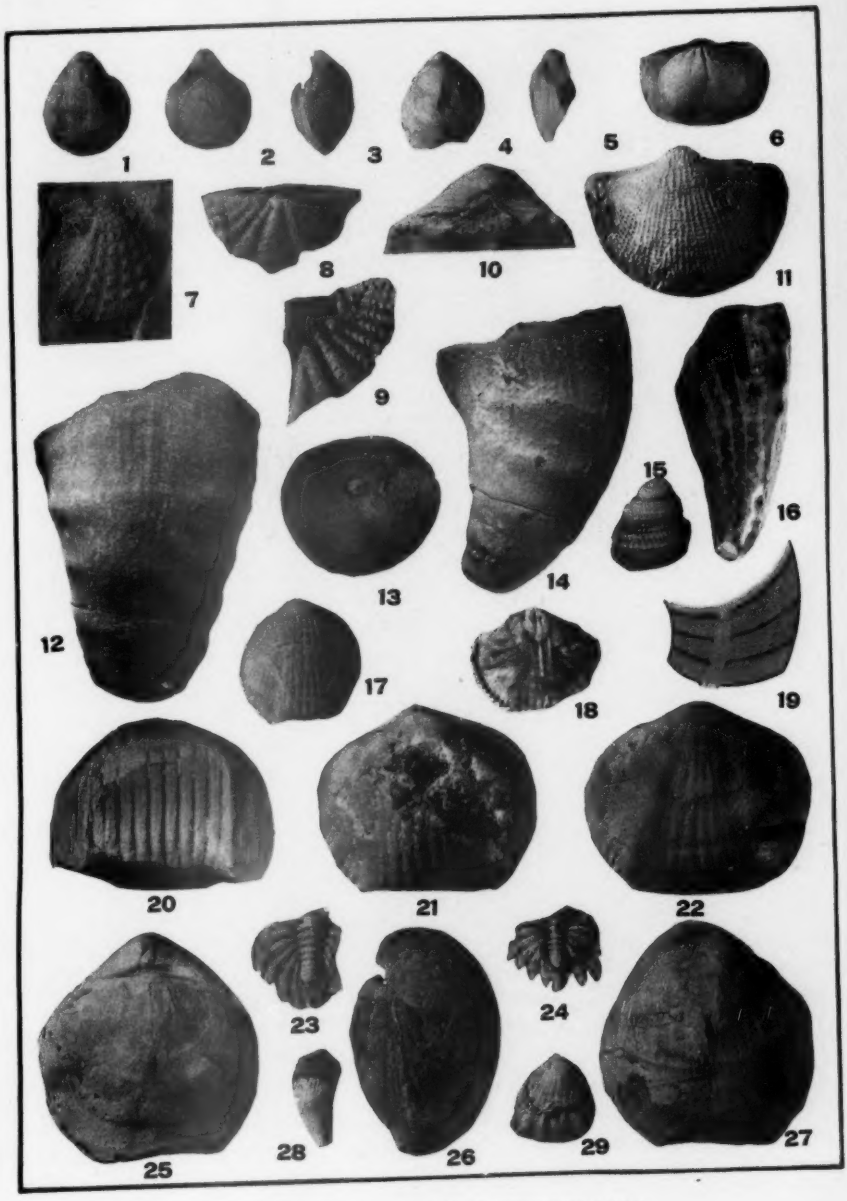
Greenops bedfordensis Willard, sp. nov.

FIGURES 23, 24. Fragmentary pygidia, × 1, from massive Tully at Schellsburg and Imler, respectively. (Holotype U. S. N. M.)

Pentamerella? sp. undet.

FIGURE 29. Fragmentary ventral valve, × 1. Specimen from the Tully shale beneath massive limestone at Imler.

(NOTE: Illustrations were made for the author by G. Arthur Cooper, with the exception of figures 12, 13, 14, and 19, which were prepared by A. K. Miller.)



FOSSILS FROM THE TULLY OF PENNSYLVANIA

AIRPLANE VIEW OF THE ABSAROKA MOUNTAINS

Southeast of Sunlight Basin. Showing characteristic "Absaroka topography." Photo by Charles J. Belden, Pitchfork, Wyoming.

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GENESIS AND STRUCTURAL RELATIONSHIPS OF THE ABSAROKA VOLCANIC ROCKS, WYOMING

BY JOHN T. ROUSE

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INTRODUCTION

PURPOSE OF STUDY AND PROBLEMS

The purpose of this study is to determine the regional structure and tectonic history of the Absaroka Volcanic Field of northwestern Wyoming including the Absaroka Mountains and parts of Yellowstone National Park (Fig. 1). The Tertiary (probably Eocene) volcanic rocks of this field attain a thickness of more than 6500 feet.

The specific problems are as follows:

1. Types of the volcanic rocks, their sequence, and the pre-volcanic topography on which they rest.
2. The origin of the volcanic rocks.
3. The relation of the volcanic rocks to the basement rocks and to the major structural features such as Heart Mountain and other thrust masses.

FIELD WORK AND ACKNOWLEDGMENTS

The writer made a detailed study of a small, but representative area of the Absaroka Volcanic Field during the summers of 1930 and 1931, and many reconnaissance trips throughout the entire field in 1932 and 1933.

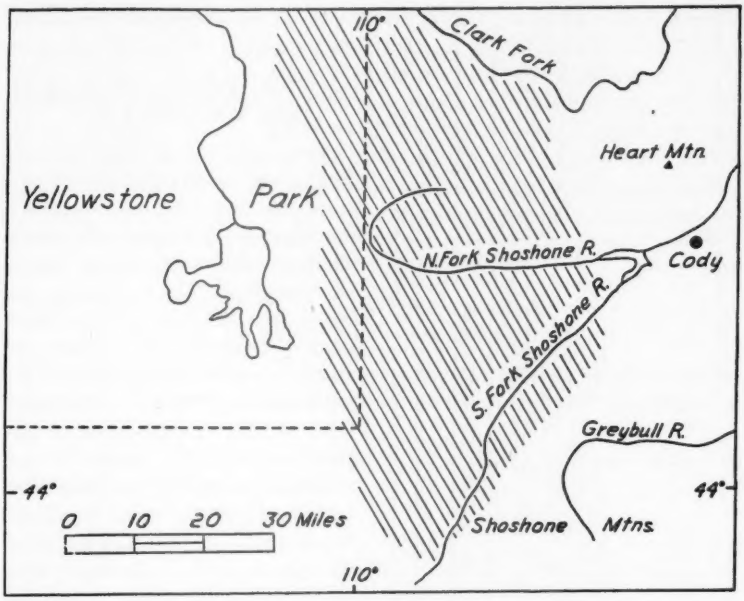

FIGURE 1.—*Sketch map of northwestern Wyoming*

Shaded portion represents area included in the Absaroka Volcanic Field.

The material for the greater part of this paper was gathered during the summers of 1934 and 1935. The field work during these latter summers was made possible by grants from the Penrose Bequest of the Geological Society of America which the writer gratefully acknowledges.

This is one part of a cooperative study, and it is not easy to cite, individually, all those who aided and offered valuable suggestions during the progress of the work. To Professors W. T. Thom, Jr., R. T. Chamberlin, and Walter H. Bucher the writer is greatly indebted for profitable field discussions and suggestions regarding the preparation of the manuscript. Much benefit was derived from field conferences with Professors O. T. Jones, of Cambridge University, and H. A. Brouwer, of the Geological Institute of the University of Amsterdam. To numerous others working on the structural problems adjacent to the volcanic field, especially to

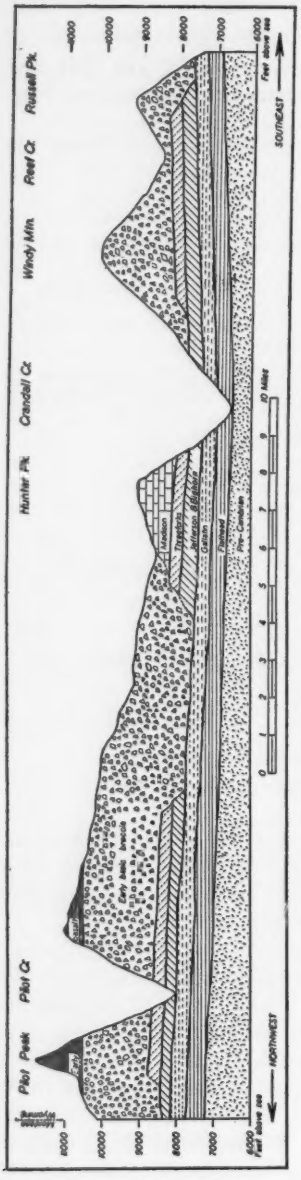

FIGURE 2.—*Cross-section along the southwest side of the Clark Fork Valley*
Showing the unconformity between the volcanic and the Paleozoic rocks.

Edward H. Stevens, the writer owes much. The field work was greatly expedited and facilitated by the splendid cooperation and interest of Mr. Merrill Snyder and many other ranch owners in the Absaroka region.

LOCATION AND BOUNDARIES OF THE VOLCANIC FIELD

As the majority of these volcanic rocks occur in the Absaroka Mountains, the area has been designated the Absaroka Volcanic Field whose northern and northeastern limits are essentially the boundary between the Absaroka and the Beartooth mountains—i.e., where the volcanic rocks abut against the pre-Cambrian rocks. Originally these volcanic rocks extended farther northeast but they did not overflow the crest of the Beartooth anticlinal uplift near the Montana-Wyoming State line, as is indicated by the absence of cobbles of volcanic rocks in Rock and other creeks which drain the northeastern slopes of the Beartooths. To the northwest and west, in the vicinity of Yellowstone Park, the volcanic rocks under consideration were intermittently buried beneath younger eruptions of rhyolite and basalt.

To the southwest the boundary is the contact with the older rocks of Cretaceous and Tertiary age. The southern and southeastern limit was taken to be approximately the headwaters of the South Fork of the Shoshone River. Time

did not permit detailed study of the Shoshone Mountains and their very similar volcanic rocks.

The eastern boundary is the rugged mountain front which forms the west and southwest border of the Bighorn Basin. Here the thick volcanic series overlaps a great variety of older sedimentary rocks, and although they now terminate abruptly, it is quite certain that the breccias formerly extended farther to the east over a part of the present Bighorn Basin. Although the volcanic rocks as a whole are relatively soft and offer little resistance to weathering and erosion, where cut by intrusives they are more resistant. Dikes and other intrusions are present to the west in contrast to their virtual absence to the east in the sedimentary rocks of the Bighorn Basin. Consequently the volcanic rocks of this former eastward extension, devoid of intrusives which would make them resistant and resting on weak sedimentary rocks, were easily undercut and removed, while the breccias and lava flows to the west remain because of more intrusions and greater original thickness.

PRE-VOLCANIC TOPOGRAPHY

The topography of the surface on which the volcanic rocks were deposited was a factor which determined the thickness of various units of the series.

The extrusion of the breccias and lavas was preceded by a period of widespread erosion as first recognized by Hague.[1] Lovering[2] pointed to the same history for the Cooke City area, Montana.

In many instances, where present streams have cut down through the covering of volcanic rocks and into the underlying Paleozoic rocks, the old land surface can be seen in cross-section in continuous exposures, showing a relief of between 1000 and 1500 feet. The most spectacular example is on the southern side of the Clark Fork River where the breccias and lavas can be seen resting unconformably on Paleozoic rocks (Fig. 2). From Cooke City the same unconformity can be seen on the north slope of Republic Mountain (Fig. 3). Numerous other examples of this spectacular unconformity might be cited in the Sunlight Basin, Wyoming, and in many other areas.

At the northwest end of Rattlesnake Mountain and Pat O'Hara Mountain the breccias rest on upper Paleozoic and Mesozoic rocks at an elevation of approximately 10,000 feet. On the North Fork of the Shoshone River, 6 to 8 miles south of these mountains, the floor of the volcanics is only 6000 feet A.T., indicating that the general surface had a relief of 4000 feet.

[1] Arnold Hague: *Description of the Absaroka quadrangle*, U. S. Geol. Surv., Absaroka folio, no. 52 (1899) p. 3.

[2] T. S. Lovering: *The New World or Cooke City mining district, Park County, Montana*, U. S. Geol. Surv., Bull. 811 (1929) p. 18.

SUBDIVISIONS AND THICKNESS OF THE VOLCANIC SERIES

GENERAL STATEMENT

Hague and the others who originally mapped parts of the area classified the volcanic rocks as follows:[3] early acid breccia, early basic breccia, early basalt sheets, late acid breccia, late basic breccia and late basalt sheets. Except for a few modifications, or local variations, these six units

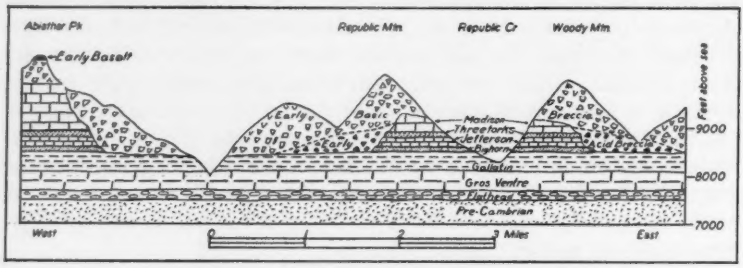

FIGURE 3.—*Cross-section along the south side of Soda Butte Creek*
In the vicinity of Cooke City, Montana, and Yellowstone National Park. Showing the unconformity between the breccias and the Paleozoic formations.

are still used as defined by Hague. This study is not concerned with the younger flows of rhyolite and basalt which are so abundant in Yellowstone National Park.

The total thickness of the volcanic series in continuous exposure varies between a maximum of 6500 feet in the central part of the field and a minimum of a few hundred feet at the periphery. Local variations are numerous as all of the units are not universally present. The total thickness obtained by a summation of the maximum thickness of each unit would exceed 11,000 feet.

TERMINOLOGY

Although all the individual pyroclastic units are dominated by breccias they contain agglomerates, tuffs, and volcanic conglomerates as well. The terminology of the pyroclastic rocks used throughout this discussion is that suggested by Wentworth and Williams[4] from whose paper the following definitions are taken.

"Agglomerate—Contemporaneous pyroclastic rocks containing a predominance of rounded or subangular fragments greater than 32 mm. in diameter, lying in an ash or tuff matrix and usually localized within volcanic necks (*Vent agglomerates*) or at a short distance therefrom. The form of the fragments is in no way determined by the action of running water, as in volcanic conglomerates, but is a primary feature determined during the actual eruption.

[3] Arnold Hague: *op. cit., geologic map.*
[4] C. K. Wentworth and Howell Williams: *The classification and terminology of the pyroclastic rocks*, Nat. Res. Coun., Bull., no. 89 (1932) p. 45-51.

"Breccia—More or less indurated pyroclastic rocks consisting chiefly of angular ejecta 32 mm. or more in diameter. If the fine tuff matrix be abundant, the term *tuff breccia* seems appropriate.

"Tuff—Indurated pyroclastic rocks of grain generally finer than 4 mm.; i.e. the indurated equivalent of volcanic ash or dust.

"Volcanic conglomerate—Sedimentary, coarse pyroclastic material containing an abundance of large, chiefly rounded, waterworn fragments. In most cases they result from the erosion and redeposition of old volcanic rocks, but they may also be formed by volcanic mud flows and by the action of running water on freshly fallen ejecta."

Better unit names for this volcanic field would be "early acid pyroclastics, early basic pyroclastics, early basalt sheets," but in order to avoid confusion the early nomenclature is retained.

CRITERIA FOR DISTINGUISHING THE UNITS

To distinguish between the acid and the basic breccias in the field is most difficult and in many instances it was found necessary to depend on microscopic studies. Hague has stated that:

"In general where both series of breccias occur together they are easily recognized by their strong contrast of color, by differences in their form of erosion, and by their marked unconformity, the earlier breccias showing evidences of extensive erosion before the pouring out of the later and more basic rock. In some instances there appear to be transition rocks, passing over from one series to the other without any marked physical or mineralogical break."[5]

It was found, however, that color and erosional forms could not be used satisfactorily. Although such features may add confirmatory evidence, the primary distinction should be made according to composition. Of the mineral composition of the acid and basic breccias, Hague writes:

"In mineral composition the acid breccias vary considerably, but consist mainly of hornblende-andesites and hornblende-mica-andesites. Flakes of dark brown biotite abound through the greater part of these breccias. Some of the most siliceous varieties carry phenocrysts of quartz, and in sufficient quantity to place the rock under the head of dacite or quartz-bearing andesite. Occasionally the more basic varieties carry a large amount of ferromagnesian minerals, when some form of pyroxene is usually found accompanying the hornblende. . . . In strong contrast to the acid breccias, the basic breccias are usually dark colored, owing to the amount of ferromagnesian minerals in the rocks. The material consists largely of hornblende-pyroxene-andesites, pyroxene-andesites, and basalts, both with and without olivine, the latter seldom occurring as an abundant mineral. Gradual transitions and slight variations may be found throughout the early basic breccias, but from one end of the range to the other the prevailing rock is pyroxene-andesite, on the one hand passing into slightly more acid breccias with a development of hornblende, and on the other hand into more basic rock with characteristic basaltic form."[6]

The writer has found that the best, and probably most certain, distinction between these two groups depends upon the presence of amphibole and

[5] Arnold Hague: *op. cit.*, p. 4.
[6] *Op. cit.*, p. 3 and 4.

biotite, or pyroxene, in the groundmass. This is thought to be a more reliable distinction than one based on the composition of the fragments in delimiting acid-basic borderline rocks. Microscopic studies have been made of definitely determined acid and basic types described by Hague, and they show a groundmass rich in amphiboles and biotite in the former and pyroxene in the latter.

The early acid breccias and the late acid breccias are indistinguishable mineralogically. This distinction can only be made from the stratigraphic relations. The same is true of the early and late basic breccias.

EARLY ACID AND INTERMEDIATE BRECCIAS

Early Acid Breccia.—The representative types are acid breccias, tuffs and agglomerates, the majority of which are well bedded. In the Absaroka region exposures are limited and small. On the Ishawooa sheet of the Absaroka folio there is only one exposure, that being found on the northwest side of the South Fork of the Shoshone River, 2 miles above Ishawooa Creek. Here the breccia is about 250 feet thick.[7]

On the Crandall sheet of the same folio, at the junction of Timber and Closed creeks, the series starts with 100 feet of well-bedded acid tuff resting on Madison limestone. The tuff is overlain by moderately coarse breccia in which the fragments are seldom larger than one inch in diameter. More than 50 per cent of the fragments in this breccia are Paleozoic limestone and almost 20 per cent of them are pre-Cambrian granites and granite gneisses. Near the top of the acid breccia the percentage of fragments of Paleozoic and pre-Cambrian rocks decreases to insignificance. The thickness of the entire acid series here is between 400 and 500 feet.

The abundance of xenoliths is a universal characteristic of the acid breccias. Although no specific descriptions of the fragments of limestone and pre-Cambrian rocks at Closed and Timber creeks have been found, Hague mentions the occurrence of numerous angular fragments of gneisses and schists in the early acid breccias.[8]

At the head of Republic Creek and in the Cooke City Mining District the early acid breccia attains a thickness of more than 1000 feet.

In Yellowstone Park the outcrops are patchy and widely separated, being confined to the following exposures: along Cache Creek, a tributary of the Lamar River, 1000 feet thick; at the northern end of Specimen Ridge a small band, 100 feet thick; on both the north and the south slopes of Crescent Hill, 1500 feet thick; and along the east slopes of Sepulchre Mountain. With the exception of the last exposure there is nothing unusual about the acid breccias, and descriptions may be found in the

[7] J. T. Rouse: *The volcanic rocks of the Valley area, Park County, Wyoming*, Am. Geophys. Union, 16th Ann. Meet., Tr. (1935) p. 275 and 276.

[8] Arnold Hague: *op. cit.*, p. 4.

works of Hague, but the breccia on the east slope of Sepulchre Mountain is, however, quite rich in xenoliths of pre-Cambrian schists.

At the extreme eastern and northeastern end of the volcanic field, in the vicinity of Pat O'Hara Mountain, the acid breccia is several hundred feet thick.

The eruptions of the acid breccias were not nearly so abundant as were those of the later volcanics. Furthermore, a period of widespread erosion followed the outpouring of the early acid breccias and preceded the extrusion of the early basic breccias, thereby accounting for the patchy distribution and variable thickness of the early acid breccias.

Intermediate Breccia.—In a few localities in Yellowstone Park there occurs, between the early acid and the early basic breccias, a transitional type of breccia which shows petrographic features common to both the acid and the basic breccia.[9] This breccia is more abundant in the Snowy Mountains, according to J. T. Wilson.[10] Its outcrops are so few in the Absaroka Volcanic Field that it will not be considered as a separate unit.

EARLY BASIC BRECCIA

Of all the units of the series the early basic breccia is most spectacular because of its variety, widespread distribution, and excessive thickness. This unit crops out throughout or underlies practically all of the Absaroka Volcanic Field. The extensive distribution of these breccias is shown on the geologic map of Wyoming.[11] It is also interesting to note that on this map the southern termination of these breccias agrees approximately with the southern boundary of the Absaroka field and that the Shoshone Mountains are composed of late acid and late basic breccias.

Near the edges of the field the early basic breccia may be only 100 feet thick, but nearer the center, in the vicinity of Dead Indian and Trout peaks, it reaches a maximum thickness of 5500 feet. In the remainder of the area the breccias thicken and thin irregularly, their thickness being controlled by the pre-early basic breccia topography and the nearness to centers of extrusion.

This unit is made up of: agglomerates and volcanic conglomerates, which are most abundant; breccias, both explosive and flow; tuffs, ash falls and sedimentary types; mud flows; and, rarely, thin flows of basalt intercalated in the series. A very striking, characteristic and common feature of this unit is a well-defined bedding.

Driving west from Cody, Wyoming, into Yellowstone Park, one cannot help but marvel, as the road winds through the pinnacles and hoodoos in

[9] *Ibid.*

[10] J. T. Wilson: *oral communication.*

[11] Geologic map of Wyoming (1925). Here the early basic breccias and early basalt sheets are mapped as one unit. Since the basalt sheets never occur alone, this map gives a good picture of the areal distribution of the breccia.

the early basic breccia, about the great abundance of coarse, well-rounded, waterlaid conglomerates that are so clearly seen from the road. They are generally present at one or many more horizons in the breccias throughout the entire field. The sizes of the boulders in these conglomerates are no less noteworthy. In the coarser types which are generally the most prevalent the boulders ranging from 1 to 4 feet in diameter (or even 10 feet in extreme cases) are all beautifully rounded. The same rounding is also observed in the finer conglomerates. It is difficult to make any general statement concerning the average dimensions of the pebbles, cobbles, or boulders as they vary so, not only over wide areas, but also in relatively small local areas.

In the agglomerates and the breccias the size of the fragments is also extremely variable, the most extreme dimensions being confined to the latter. The largest fragment, 175 by 50 feet in cross-section, of volcanic rock in the breccia was found in the vertical cliffs on the north side of the South Fork of the Shoshone River just below Cabin Creek. Larger fragments of limestone blocks, which may be 50 by 300 feet in cross-section or in extreme cases have dimensions several times as large, are conspicuous in the breccias. The fragments in the agglomerates of this unit average 5 to 7 feet in diameter.

In all these coarser pyroclastics, just described, the cement or matrix is a fine tuffaceous material of essentially the same composition and texture as the individual tuff beds which are also a very important and widespread constituent of the early basic breccia unit.

The tuffs are either the product of ash falls or of the reworking and subsequent deposition of these ash falls by water. In certain areas some of these tuffs are characteristically present at the base of the early basic breccias and are so thick over limited areas that they have been placed under a separate subdivision, "early basic tuffs."[12] Such a subdivision will not, however, be used, because these tuffs are limited essentially to the areas around Valley Ranch on the South Fork of the Shoshone River and Sunlight Ranch on Sunlight Creek. In the Valley area they are significant as they indicate that volcanic activity paused, and activity was dormant long enough to allow some deformation and erosion to take place before the coarse breccias were erupted. Throughout the greater part of the field the volcanic tuffs are present at no regular horizon or horizons, but are scattered at random throughout the entire unit.

In a few localities, such as Sheep Mountain and the Sunlight area, some flows of basalt are present in this unit. These are generally quite thin (10± feet), each individual flow being separated by breccia. No more than five or six of these thin flows were seen in any one section.

[12] J. T. Rouse: *op. cit.*, p. 276.

The following sections (Tables 1 and 2) show the varying types of pyroclastic rocks that make up typical sections of the unit designated as the early basic breccia. Both sections are well bedded.

TABLE 1.—*Section of early basic breccia exposed on the northwest side of the South Fork of the Shoshone River, west of Valley Ranch.*

Feet	
60	(6) Coarse green tuffs and tuffaceous conglomerates.
200	(5) Explosive volcanic breccia, relatively small angular fragments averaging 6 to 8 inches in diameter.
225	(4) Alternating beds of explosive breccia and volcanic conglomerate, 10 to 20 feet thick. The fragments and cobbles average 8± inches in diameter. Conglomerates more abundant at top.
20	(3) Fine lithic tuffs.
75	(2) Volcanic conglomerate with texture of gravel. Some tuff beds, 5 to 10 feet thick, intercalated with the conglomerate.
	SLIGHT UNCONFORMITY
850	(1) Tuff—Mainly water-laid, with fossil leaves and some fresh-water shells. Many of the beds show good cross-bedding. Occasional beds of tuff deposited as direct ash falls. Near base, two separate beds of volcanic conglomerate with thicknesses of 10 and 20 feet respectively. In thin conglomerate, small pebbles; in thick one, cobbles 8 to 12 inches are common with rare boulders measuring 2 feet in diameter. (On the map of the Valley area, this is designated "early basic tuff."[18])

TABLE 2.—*Section of early basic breccia exposed on southeast side of Jim Mountain, North Fork of the Shoshone River, approximately 20 miles west of Cody, Wyoming.*

Feet	
300	(9) Explosive breccia—fragments 8 to 12 inches.
35	(8) Volcanic conglomerate—large (average 2 feet in diameter) boulders all well rounded.
200	(7) Explosive breccia—same as 9.
250	(6) Volcanic conglomerate—at base a heavy bed, 20 feet thick, with boulders 1 to 2 feet in diameter. Remainder of conglomerate has texture of a coarse gravel.
80	(5) Alternating beds of volcanic conglomerate and tuff. Tuff beds average 5 feet in thickness, conglomerates 3 feet. Boulders of conglomerate approximately one foot in diameter. At base of this group the cobbles are subangular rather than round.
90	(4) Explosive breccia—angular fragments 3 to 12 inches in diameter.
50	(3) Lithic tuff with occasional thin beds of fine explosive breccia.
700	(2) Explosive breccia—Upper parts essentially the same as 9. Near the base some fragments of limestone (as large as 5 feet in diameter) together with smaller, but more abundant fragments of quartzite, gneiss, and some mica schist.
	UNCONFORMITY
	(1) Wasatch.

[18] *Ibid.*

EARLY BASALT SHEETS

These lava flows, averaging 1000 feet in aggregate thickness, occur either as rather extensive outcrops or as outlying patches throughout the entire field. In the northern and central parts of the field their absence is due to extensive erosion after the completion of the volcanic cycle. To the southwest, in Yellowstone Park, the present streams have not cut through the pyroclastics overlying the basalt sheets, and exposures here are wanting.

The early basalt sheets are made up of a succession of lava flows varying from 50 to 100 feet in thickness. As the name might imply, the majority of the flows are of basalt, but some flows of absarokite and andesitic-basalt are present. A great many of these flows exhibit good columnar jointing, and in all cases they crop out in a series of vertical cliffs. In some areas [14] the flows have been subdivided into six groups, on the basis of their stratigraphic position and mineral composition, and throughout much of the area they produce six separate, step-like cliffs (Pl. 2, fig. 2). These basalts are of particular stratigraphic importance as they definitely mark the top of the early series of volcanic rocks.

LATE ACID BRECCIA

As Hague pointed out, the late acid breccia is much more widely distributed and is much thicker than the early acid one. Such high peaks as Pyramid, Silver Tip, and Sailor in the southeast corner of the Canyon quadrangle and Avalanche, Hoyt, Reservation, and Atkins in the southeast portion of the Lake quadrangle of the Yellowstone Folio are composed of late acid breccia. Practically all the outcrops of this breccia are found in the area occupied by these peaks and in a large area in the vicinity of Overlook Mountain on the west side, center, of the Ishawooa quadrangle.

The thickness of these breccias ranges from 500 to 2500 feet; the maximum thickness is exposed on the south side of Middle Creek in the vicinity of Reservation Peak. From the road into Yellowstone Park, just after leaving the East Entrance and starting up the grade to Sylvan Pass, the steep cliffs and pinnacles of the late acid breccia can be seen rising steeply on the south side of Middle Creek.

The composition of the late acid breccia does not differ appreciably from the early acid breccia, except that the former contains fewer fragments of pre-Cambrian and Paleozoic rocks. The textural difference is quite striking, the late acid being much coarser than the early acid breccia. Although the fragments are measured in terms of inches in the early ones, they are measured in feet in the later breccias. The late acid unit is composed, in order of abundance, of breccias, agglomerates, and volcanic con-

[14] *Ibid.*, p. 279-280.

FIGURE 1. BEDDING IN THE EARLY BASIC BRECCIAS ON THE SOUTHEAST SIDE OF JIM MOUNTAIN

FIGURE 2. EXPOSURES OF THE EARLY BASALT SHEETS
On Deer Creek, a tributary of the South Fork of the Shoshone River.

EARLY BASIC BRECCIAS AND BASALT SHEETS

FIGURE 1. LIMESTONE BLOCKS IN EARLY BASIC BRECCIAS
On Post Creek, a tributary of the North Fork of the Shoshone River. Note the large blocks with varying dips in center; smaller blocks in breccia to left. Photo by Walter H. Bucher.

FIGURE 2. NORTHWEST SIDE OF THE SOUTH FORK OF THE SHOSHONE RIVER
Showing relations of early basic breccia to the thrust masses. (MC) Cretaceous and Wasatch; (B) early basic breccia; (P) thrust sheets of Paleozoic limestone; (P^1) limestone blocks incorporated in the breccia; (dashed line) th t fault plane; (solid line) base of early basic breccia. Length of panorama is approximately 8 miles.

VIEWS ALONG POST CREEK AND THE SHOSHONE RIVER

glomerates. The individual fragments in the breccias and agglomerates are as large as 8 feet and in exceptional cases may be even larger.

LATE BASIC BRECCIA

The late basic breccia is second only to the early basic breccia in areal distribution and thickness. In thickness it ranges from 2000 to 2700+ feet, most of the sections being at least 2500 feet thick. A description of this unit would be practically identical with that previously given for the early basic breccia except that volcanic conglomerates are much more characteristic and prevalent in the lower horizons of this late basic breccia.

The late basic breccia is composed of breccias, conglomerates, tuffs, and some agglomerates. In the coarse pyroclastics the fragments have essentially the same dimensions as those of the early basic breccias, but there are no abnormally large fragments in this latter unit. Several sections of the late basic breccia are shown in Tables 3 and 4.

The base of this unit is nearly always characterized by either a brilliantly white tuff, 100 to 250 feet thick, or a greenish volcanic conglomerate in which the pebbles are rounded to the extent that they resemble perfect spheres. The pebbles in such conglomerates are not large (1 to 3 inches in diameter).

TABLE 3.—*Section of late basic breccias at the headwaters of Aldrich Creek, a tributary of the South Fork of the Shoshone River*

Feet	
300	(7) Explosive breccia and lithic tuffs in alternating beds. Breccias are 10 to 20 feet thick—Tuffs, subordinate in beds 5 to 10 feet.
300	(6) Explosive breccia—Fragments of average size, 6 to 12 inches in diameter.
10	(5) White tuff.
500	(4) Volcanic conglomerate—Texture of ordinary gravel with occasional boulders 1 foot in diameter. Very little matrix as cement in this conglomerate.
100	(3) Explosive breccia, light colored, fragments 1 to 2 inches in diameter.
225	(2) White tuff.
	(1) Early basalt sheets.

TABLE 4.—*Section of part of late basic breccia on the southwest side of Piney Creek, a tributary of the Greybull River, approximately 25 miles west of Meeteetse, Wyoming*

Feet	
200	(6) Volcanic conglomerate with large rounded boulders but not as well bedded as 4.
20	(5) Gray tuff.
100	(4) Volcanic conglomerate—Perfect rounding of pebbles and boulders, together with good bedding. Some of the boulders measure 15 by 20 feet. Pebbles at base of conglomerate, with coarser beds at the top.
90	(3) White, well-bedded tuff.
60	(2) Greenish volcanic conglomerate. Pebbles of average size.
	(1) Early basalt sheets.

Before ending the discussion of this unit an engraver's error on the Lake Sheet of the Yellowstone Folio should be noted. This is done in order that the reader will not be confused as to the sequence of rocks at the headwaters of Middle Creek in the northeast corner of the sheet. Going up the section along the road from the East Entrance of Yellowstone Park to Sylvan Pass the stratigraphic sequence is early basic breccia, early basalt sheets, late acid breccia, and late basic breccias. On the map this late basic breccia, on top of the early basalt sheets, is designated as early basic breccia rather than late basic breccia. The description of the Sylvan intrusive rocks, which cut the breccias in this locality, reads: "dike rocks varying from diorite to granite-porphyry breaking through late basic breccia near Sylvan Pass."

But the geologic map does not show any late basic breccia in the vicinity of Sylvan Pass. The one large area of breccia including Top Notch Peak, Grizzly Peak, and Sylvan Pass, together with the two smaller patches of breccia to the southeast should be designated late basic rather than early basic breccia.

LATE BASALT SHEETS

The outpouring of the late basalt sheets brought to a close that phase of the volcanic cycle which is presented in this paper. These lava flows are confined to the Ishawooa sheet as remnants on the high divide separating the tributaries of the Yellowstone River from those of the North and South forks of the Shoshone River. They are composed of a series of basalt flows totaling between 200 and 500 feet in thickness. Since extrusion, these flows have been extensively eroded.

INTRUSIVE ROCKS

The entire volcanic series is cut by innumerable intrusive bodies of different shape, size, composition, and age. Some cut only the early units; others cut both the early and the late units of the volcanic series. As this paper is concerned primarily with the volcanic rocks the many intrusives will not be described. For descriptions of some of them the reader is referred to other publications.[15]

[15] T. S. Lovering: *New World or Cooke City mining district, Park County, Montana,* U. S. Geol. Surv., Bull. 811-A (1930) p. 1-89.

Arnold Hague *et al.: Geology of the Yellowstone National Park,* U. S. Geol. Surv., Mon. 32, pt. 2 (1899) p. 60-149, 215-356.

J. P. Iddings: *The eruptive rocks of Electric Peak and Sepulchre Mountain, Yellowstone National Park,* U. S. Geol. Surv., 12th Ann. Rept., pt. I (1891) p. 577-664.

J. T. Rouse: *The structure, inclusions, and alteration of the Deer Creek intrusive, Wyoming,* Am. Jour. Sci., 5th ser., vol. 26 (1933) p. 139-146.

J. P. Iddings: *Yellowstone National Park; igneous rocks,* U. S. Geol. Surv., Yellowstone National Park Folio, no. 30 (1896) p. 6.

Arnold Hague: *Description of the Absaroka quadrangle,* U. S. Geol. Surv., Absaroka Folio, no. 52 (1899) 6 pages.

AGE OF THE VOLCANIC ROCKS

The age of this entire series of volcanics is still an open question. Knowlton assigned an Eocene (?) (Fort Union) age to the early acid breccia and a Miocene age to the basic breccias on the basis of plant assemblages.

"From this evidence it appears that the flora of the early acid breccias in the Yellowstone National Park finds its closest affinity with the flora of the Fort Union Group, and is unhesitatingly referred to that age. . . .

"The preponderance of evidence points to the similarity of age between the flora of the basic (breccia) series and that of the Auriferous gravels of California. The fixing of the exact age of the Auriferous gravels is not a difficult matter. They at first were supposed to be Lower Pliocene in age, but the latest evidence, derived from a more or less complete restudy of the abundant flora, together with a thorough investigation of the stratigraphy, makes it reasonably certain that it is Upper Miocene. This view is taken in the present instance, and this flora in the Yellowstone National Park is referred to as Upper Miocene." [16]

About the Lamar River flora of the early basic breccia in Yellowstone Park, Read concludes:

"The flora is of a transitional type, showing on the one hand a marked resemblance to a certain early Eocene flora of Western America and on the other hand to well known middle Tertiary floras. It must be regarded as much older than the Upper Miocene to which it has been referred—either Lower Oligocene or Upper Eocene. Four species of coniferous woods are recognized in the floras, these generally identical with forms growing in the modern redwood forests." [17]

In the same paper, Read quotes the following written communication from R. W. Chaney:

"During the past ten years evidence has accumulated which indicates that the Auriferous gravels contain several distinct floras in horizons ranging from Eocene to Miocene." [18]

A collection of leaves from the basal tuffs of the early basic breccias near Valley, Wyoming, on the South Fork of the Shoshone River, and from the coarser breccia which overlies the thrust sheet of Sheep Mountain west of the Shoshone reservoir, has been studied by Erling Dorf, of Princeton University. From a tentative determination of these leaves, Dorf is of the opinion that they represent a flora of Fort Union or Early Eocene age.

On a different basis, Jones and Field [19] have pointed out, in their study of the geologic history of the Grand Canyon of the Yellowstone River in Yellowstone Park, that a complex series of events followed the accumula-

[16] F. H. Knowlton: *Geology of the Yellowstone National Park*, U. S. Geol. Surv., Mon. 32, pt. 2 (1899) p. 788-791.

[17] C. B. Read: *Fossil floras of Yellowstone National Park*, Part 1, *Coniferous woods of the Lamar River flora*, Carnegie Inst. Wash., Publ. no. 416 (1935) p. 10.

[18] *Op. cit.*, p. 5.

[19] O. T. Jones and R. M. Field: *The resurrection of the Grand Canyon of the Yellowstone*, Am. Jour. Sci., 5th ser., vol. 17 (1929) p. 261-279.

tion of the late basalt sheets. To allow time for these events they favor dating the breccias as Eocene.

In view of these opinions the writer favors assigning the breccias and lavas of the Absaroka Volcanic Field to the Eocene epoch. There is, of course, a possibility that they might be continued into the Oligocene epoch.

TIME REQUIRED FOR ACCUMULATION OF THE VOLCANIC SERIES

The long period of volcanic activity in this field was spasmodic and broken by frequent intervals of relative quiescence during which volcanic conglomerates or fine volcanic sediments were deposited by non-volcanic processes. The long periods of extensive erosion (see table 5) separating many of the units also indicates a lapse of much time during the volcanic cycle. Among the non-volcanic deposits are the famous fossil forests of Yellowstone National Park. Perhaps the most spectacular of these is the widely known "Fossil Forest" on the northern slope of Amethyst Mountain, described by Knowlton.[20] Here at least fifteen different forests, each at a successively higher elevation, have been buried by the early basic breccias. These fifteen separate fossil forests, each containing unusually large trees, would in itself indicate that early basic breccia time was long.

SUMMARY OF STRATIGRAPHIC SEQUENCE

The volcanic sequence and order of events in the Absaroka Volcanic Field is summarized in Table 5.

TABLE 5.—*Stratigraphic sequence and geologic history of the Absaroka Volcanic Field*

16	Rhyolite and recent flows in Yellowstone Park
15	Widespread erosion
14	Warping
13	Outpouring of late basalt sheets
12	Accumulation of late basic breccia
11	Erosion
10	Accumulation of late acid breccia
9	Outpouring of early basalt sheets
8	Minor erosion
7	Tilting and local folding
6	Accumulation of early basic breccia
5	Local erosion
4	Local folding
3	Local deposition of early basic tuff
2	Extensive erosion
1	Accumulation of early acid and intermediate breccias

[20] F. H. Knowlton: *op. cit.*, p. 755-760.

For excellent and unusual photographs, see Wendell and Lucie Chapman: *The petrified forest*, Nat. Hist., vol. 35 (May 1935) p. 382-394.

ORIGIN OF THE BRECCIAS

VIEWS OF EARLY WRITERS

According to the early work of Hague, Iddings, and others the volcanic ejectamenta were thrown from many vents scattered over the area. Most of these vents have been obscured by the successive accumulations of later material. The early descriptions imply that the vents were variable in size, yet only the unusually large ones, such as the Crandall, Electric Peak, and Sepulchre Mountain,[21] have been described in detail. It has been found that many of the smaller vents, which are certainly very significant, can also be located (Fig. 9). The processes by which the pyroclastics were brought to the surface will be considered first, and this will be followed by a discussion of the processes responsible for their dispersal over large surface areas.

CRITERIA FOR RECOGNIZING VENTS

In this volcanic field the location of the loci of extrusion of the pyroclastics is hampered by the great thickness of volcanic material. Volcanic necks and cones do not stand out as conspicuous topographic features as they do in some volcanic fields. In some instances the dips of the volcanic beds may have some relation to the volcanic vents. These, however, should be used cautiously as they may represent initial dips on a sloping pre-volcanic surface or may even be the result of deformation of the pyroclastics after extrusion.

The following criteria have been used to recognize places of egression of the pyroclastics.

1. In volcanic outbursts the larger fragments will be closely associated with the vent, and as the distance from the vent increases the fragments in the explosive breccia should decrease in size.

2. If unusually large proportions of foreign rocks are found as xenoliths in the explosive breccia, it is certain that the vent broke through country rock of the character and age represented by these xenoliths. Such a criterion will frequently confine the vent to a relatively small area.

3. Vent agglomerates indicate that a vent was situated at the present outcrop of such an agglomerate.

4. Thin basaltic lavas, 5 to 10 feet thick, interbedded with the breccias and very local in areal extent, could not have flowed far from the place of eruption. It is not safe to use this criterion alone, but if used with other criteria it adds confirmatory evidence.

5. Dikes of intrusive breccia, cutting through older rocks, are interpreted as small feeders through which the breccias reached the surface.

[21] J. P. Iddings: *The dissected volcano of Crandall Basin, Wyoming*, U. S. Geol. Surv., Mon. 32, pt. 2 (1899) p. 215-269; *The igneous rocks of Electric Peak and Sepulchre Mountain*, U. S. Geol. Surv., Mon. 32, pt. 2 (1899) p. 89-149.

6. Some intrusive igneous masses may be related to old vents or volcanoes. The existence of such a body in itself does not prove the presence of a former vent, as the entire field is cut by abundant intrusives, the majority of which are ordinary stocks, laccoliths, bysmaliths, which show no evidence of having had an outlet at the surface.

7. Dikes radiating from a common central area generally have a connection with a locus of extrusion.

DESCRIPTIONS OF SOME REPRESENTATIVE VENTS

Crandall.—There were hundreds of small vents, together with a few volcanoes of moderate size, throughout the Absaroka Volcanic Field, each throwing forth large quantities of volcanic ejectamenta.

According to Iddings the large intrusive mass of coarsely crystalline gabbro and diorite, now exposed on Hurricane Mesa (Crandall quadrangle, Wyoming), represents the core of a large dissected volcano which supplied volcanic ejectamenta for a large area.[22] He states that this Crandall volcano had a radius of 20 miles and rose to a height of 13,400+ feet above the land surface or approximately 21,000 feet above sea level.[23] His evidence for such a volcano may be summarized as follows:

1. Abundant dikes radiate outward from the central intrusive mass of Hurricane Mesa.

2. This intrusive mass is the core of the volcano or the conduit through which lavas moved to the surface or from which they escaped in lateral fissures of the surrounding rocks.

3. The lava eventually solidified in this core and is now represented by the coarsely crystalline gabbro and diorite. The solidification took place 10,000 to 12,000 feet below the level of the ancient crater.

A detailed study of this region by the writer has shown that:

1. There is a general radiating pattern of the dikes, outward from Hurricane Mesa, but these are not as conspicuous as the original description and map indicate. Dikes not fitting into the radial pattern are exceedingly numerous.

2. Coarsely crystalline gabbros and diorites, at elevations as high as Hurricane Mesa (11,000 feet) are not unique in the Absaroka Mountains. Intrusive masses, in no way related to old volcanic cores, equally as coarse grained as those of Hurricane Mesa abound at high elevations throughout these mountains.

3. There is no radial dip of the pyroclastics from the supposed core or center of the large volcano. The breccias are well bedded, but their attitude is essentially horizontal.

[22] J. P. Iddings: *The dissected volcano of Crandall Basin, Wyoming*, U. S. Geol. Surv., Mon. 32, pt. 2 (1899) p. 215-269.

[23] The present elevation of the base of the volcanics varies between 7,000 and 8,000 feet A. T.

4. Six to eight miles northeast of the proposed core the volcanics end near the Clark Fork River and continuing northeast across the river the present country rock is pre-Cambrian granite and granite gneiss and no volcanic rocks are present. The cross-sections of the Crandall volcano [24] show that the breccias were more than 13,000 feet thick at the highest part of the volcano, directly above Hurricane Mesa, and immediately above the Clark Fork River they were approximately 9000 feet thick. If the volcano had been this large the breccias would have covered the pre-Cambrian surface well beyond the present divide between Clark Fork in Wyoming and Rock Creek in Montana, yet there is a complete absence of any volcanic material in the Rock Creek drainage. Therefore, it is assumed that although the breccias undoubtedly overlapped the pre-Cambrian rocks to the northeast, they never reached as far as the present Clark Fork-Rock Creek divide. If this reconstruction of the volcano is correct the northeast slope would have been abnormally steep and not in accord with the slopes of present-day volcanoes.

While the foregoing observations do not totally disprove the existence of the major volcano, they do cast some doubt on it. There were relatively small, active vents in this area, but they did not reach the magnitude of a volcano of the size Iddings suggested.

The small outcrop of early acid breccia in this vicinity shows the physical events accompanying the initial periods of volcanic activity. At the junction of Closed and Timber creeks this breccia is 400 to 500 feet thick. The basal part of this unit, resting on an isolated remnant of Madison (?) limestone, is composed of fine acid tuff, 100 feet thick. Overlying this tuff is a breccia, 125 feet thick, composed of angular fragments, one inch or less in diameter. Of these fragments, 55 per cent are Paleozoic limestones, 30 per cent are volcanic rocks, and 15 per cent are pre-Cambrian granites and gneisses. The fragments constitute 40 per cent of the breccia; the remaining 60 per cent is a tuffaceous matrix. Higher in the section the breccia progressively coarsens, and in the next 100 feet the angular fragments are 3 to 4 inches in diameter. Here the fragments are 95 per cent volcanic rocks, 4 per cent pre-Cambrian rocks, and 1 per cent Paleozoic limestones. The tuffaceous matrix forms 40 to 50 per cent of the breccia, and the fragments the remainder. In the top portion of the early acid breccia, as well as in the overlying early basic breccia, the large fragments, 1 to 2 feet in diameter, are practically all of volcanic rocks.

The basal tuff, in the section just discussed, represents the initial eruption of a nearby vent. The foreign fragments in the overlying breccia indicate that the vent broke through limestone country rock. This second

[24] J. P. Iddings: *op. cit.*, pl. 32, Sect. E-F.

stage (Fig. 4) of volcanism, immediately following the first, was witnessed by increased activity, and the local vent widened at the expense of the Paleozoic country rock. As the vent widened [25] the ejectamenta covered the surrounding areas and coated the walls of the vent (Fig. 4). With the limestone country rock thus protected, later eruptions were breccias composed dominantly of volcanic rock fragments together with rare lime-

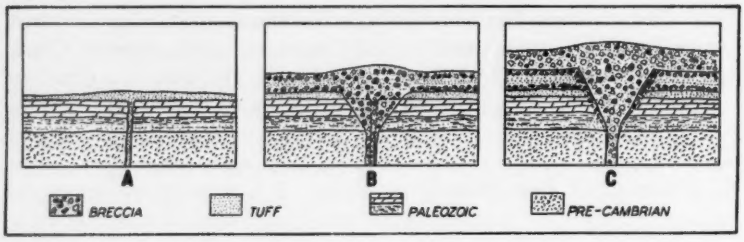

FIGURE 4.—*Diagrams illustrating the stages of development of a volcanic vent*

(A) Initial outbreak with the deposition of tuff. (B) Continued activity widens the vent at the expense of the country rock, hence many fragments of the Paleozoic and pre-Cambrian rocks in the ejectamenta. (C) Final activity results in the extrusion of breccia in which volcanic fragments are dominant as the country rock is protected by materials from earlier eruptions and the vent has attained its maximum width.

stone fragments and occasional pre-Cambrian ones carried up from considerable depth.

Cooke City.—As Lovering's report [26] on the Cooke City district is concerned primarily with the ore deposits and structure, little space is devoted to the volcanic rocks of the district. As to the origin of the early acid and early basic breccias, which are both present in this area, he states:

"The vents from which the early acid breccia came are not known. . . . The materials of which it (early basic breccia) is composed may have come from the Crandall volcano, 15 miles to the south.[27]

The breccias of this area are not intimately related to the postulated Crandall volcano but are due rather to local eruptions through small vents and fissures in the Cooke City district. On the east side of Republic Creek, approximately 2 miles south of Cooke City, two basic breccia dikes, each 25 to 30 feet wide, cut across the Madison limestone and dis-

[25] In the description of the Cripple Creek volcano, Loughlin and Koschman state that the rising lava took advantage of fissure zones "and as they approached the surface they erupted with explosive force and produced vents whose upper part flared considerably and whose lower parts were steep walled" [G. F. Loughlin and A. H. Koschman: *Geology and ore deposits of the Cripple Creek District, Colorado*, Colorado Sci. Soc., Pr., vol. 13, no. 6 (1935) p. 291-292].

[26] T. S. Lovering: *The New World or Cooke City mining district, Park County, Montana*, U. S. Geol. Surv., Bull. 811 (1930) p. 1-89.

[27] *Op. cit.*, p. 30-32.

appear in the overlying basic breccia. The breccia dikes have chilled edges which, microscopically, show a large amount of glass and flowage lines parallel to the walls of the dike. These dikes are small conduits through which some of the pyroclastics were carried to the surface. These two small dikes would not account for the extrusion of a large quantity of breccia, but their presence, together with similar ones in other areas, substantiates the belief that eruptions through small vents were significant and important sources. Hundreds of similar channels must have been present throughout the Absaroka Volcanic Field and were responsible for the extrusion of much volcanic material.

There were also a number of vents of moderate size in this area. The diameters of the base of these would probably be measured in thousands of feet. It may seem too hypothetical to postulate the presence of vents unless the exact center of eruption can be located. That, however, is impossible. Thousands of feet of breccias and lavas would have to be eroded before an accurate ground-plan of the area could be seen. What these volcanic rocks cover can only be inferred indirectly. Interpretations must be based on the scant evidence found in the deep, steep canyon and valley walls. Orifices which supplied the materials for the early acid breccias were not necessarily the same as those supplying the late basic breccia, as a long period of quiescence and erosion separates the two units.

Some of the early acid breccias on Republic Mountain may have been thrown from a vent a mile or less to the southwest. On the north front of this mountain the basal early acid breccias are flow breccias. Deformation of the underlying Paleozoic limestones, by the breccias, indicates that these flows were moving from the southwest to the northeast against a rather steep topographic rise (Fig. 7). Alignment of limestone fragments in these flows further verifies this direction of movement. In the upper bedded portion the early acid breccia dips 15 to 20 degrees to the southwest; this is interpreted as a dip back into the vent. Similar dips have been figured by Williams in the Navajo-Hopi country.[28]

The size of the fragments in the explosive early basic breccia of Republic Mountain, which rests unconformably on the early acid breccia, suggests extrusion from a nearby vent. Rounded pieces of basalt, 3 to 4 feet in diameter, together with some as large as 10 feet in diameter, could not have been hurled for an appreciable distance. These large fragments are confined to a small area on Republic Mountain.

White Mountain Volcano.—This volcano is located in the Sunlight Basin (east side, center of the Crandall sheet) and occupies part of an area studied by Willard H. Parsons for a doctor's dissertation at Prince-

[28] Howel Williams: *Pliocene volcanoes of the Navajo-Hopi Country*, Geol. Soc. Am., Bull., vol. 47 (1936) p. 112, fig. 4.

ton University. To him the writer is indebted for much of the following information.

The volcanic plug, represented by gabbro intrusions cross-cutting the Paleozoic limestones of White Mountain, is surrounded by explosive breccias. The volcanic activity was sufficient to metamorphose a limited

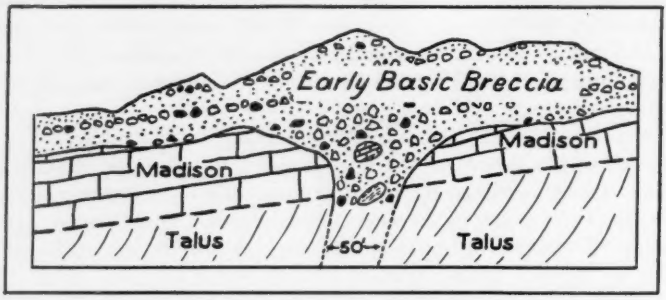

FIGURE 5.—*Breccia dike cutting across part of the thrust mass on the southeast side of Sheep Mountain*

area of the surrounding limestones which are now brilliantly white and show, in many instances, complete recrystallization. Hundreds of dikes radiate from this volcanic center. These radiating dikes cover an area within a radius of 2½ miles to the north, northwest, and southeast, and 4½ miles to the west, southwest, and south of the plug.

The breccias in this district are all early basic which rest, for the greater part, on Paleozoic limestones. South of the volcano, on the south side of Sunlight Creek, the base of the breccia is composed of several hundred feet of basic tuff which is equivalent to the early basic tuff of the Valley area, Wyoming. Aside from this local area of tuff the volcanic series is predominantly explosive breccia of the Vulcanian type with some of the Pelean type. In a limited area immediately adjoining the plug and almost due west of it the flow breccias alternate with thin lava flows, 10 to 15 feet thick. Here the breccias and lava flows strike N. 10°E. and dip north, away from the vent, 6 to 7 degrees.

A much larger volcano, the Sunlight volcano near the head of Sunlight Creek, has been described by Parsons.[29]

South Fork of the Shoshone River.—Sheep Mountain, west of the Shoshone Reservoir, is composed of large overthrust masses of Paleozoic limestone. These limestones, are, in turn, overlain by early basic breccias. On its southeast face, one mile northeast of Bear Creek, a breccia dike cuts across the thrust mass (Fig. 5). The contact of the thrust mass and

[29] W. H. Parsons: *Volcanic centers of the Sunlight area, Wyoming* [abstract], Geol. Soc. Am., Pr. 1936 (1937) p. 93.

the underlying Wasatch is obscured by talus, and the cross-cutting relations of the dike and the Wasatch are not visible. This dike of explosive breccia is 50 feet wide and contains, in addition to volcanic fragments, blocks of limestone and black shale (maximum size 2 by 4 feet) in a tuffaceous matrix. The black shale fragments prove that this is a breccia

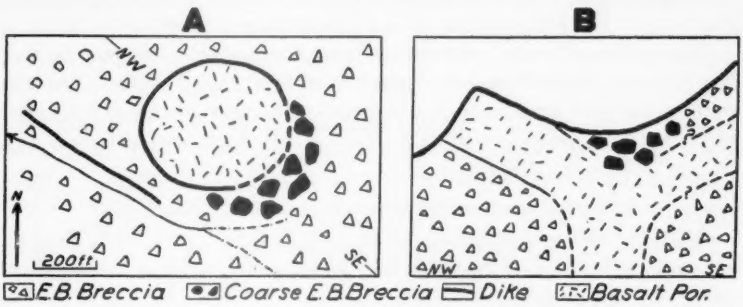

FIGURE 6.—*Sketch map and cross-section of volcanic vent on Aldrich Creek*

(A) Areal sketch map showing the position of the roughly circular tower of basalt porphyry. The tower is surrounded by early basic breccia cut in one place by a vertical basalt dike. (B) Cross-section showing probable relation of the basalt porphyry to the volcanic vent or neck.

dike rather than breccia filling a cavity in the limestone thrust mass. There are no black shale horizons in the Paleozoic rocks above the point where this shale was found, but there are numerous such horizons in the Mesozoic rocks beneath the thrust mass. The shale was torn loose from the lower parts of the conduit as the breccia made its way to the surface through this dike.

The remnant of a small vent is found just north of the headwaters of Aldrich Creek, a tributary of the South Fork of the Shoshone River. This is in the form of an isolated mass of columnar, porphyritic olivine basalt whose shape resembles, in miniature, the classic Devil's Tower of Wyoming. The basalt, 125 feet thick, occupies a small area (400 by 500 feet). It rests on a surface that slopes to the southeast, and the columns of basalt are correspondingly inclined 35 degrees from the vertical (Fig. 6). The diameters of the individual columns vary between 2 and 6 feet. Similar arrangements of columns have been described in the Mount Taylor region, Navajo-Hopi country, and at Devil's Tower.[30] The base of the basalt is dense and devoid of any amygdules; at the top it is extremely

[30] D. W. Johnson: *Volcanic necks of the Mount Taylor region, New Mexico*, Geol. Soc. Am., Bull., vol. 18 (1907) p. 303-324.

Howell Williams: *op. cit.*, p. 111-172.

C. E. Dutton and G. M. Schwartz: *Notes on the jointing of the Devil's Tower, Wyoming*, Jour. Geol., vol. 44 (1936) p. 717-729.

vesicular. This, together with cross joints that are concave upward, indicates that the top of the basalt was at the surface, or nearly so, and cooled downward. On the southeast side of the vent the early basic breccia is extremely coarse and contains fragments of vesicular basalt, 2 to 4 feet (and sometimes larger) in diameter.

The possibility of a vent between Deer and Ishawooa creeks (Ishawooa quadrangle) has been mentioned in a previous publication.[31]

Descriptions of other vents would involve unnecessary repetition, and it is believed that sufficient evidence has been presented to show that the pyroclastics were erupted from numerous small vents as well as volcanoes that may have reached moderate sizes. These vents and volcanoes are located on the map, Figure 9.

CLASSIFICATION ACCORDING TO METHODS OF ACCUMULATION

Explosive Processes.—The areal distribution of the breccias is dependent on the methods of accumulation, and the following classification is based on such methods.

The pyroclastics due to explosive forces comprise widely different textural types. The material projected by explosions subsequently fell throughout most of the area forming breccias, agglomerates, or tuffs.

The explosive breccias are, in the main, well bedded and composed of angular fragments of volcanic rocks of varying composition embedded in a tuffaceous matrix. In the field it is frequently quite difficult to distinguish explosive breccias from flow breccias because the former may be indurated to such an extent that they have many macroscopic characteristics of the flow type.

In thin sections the fragments in the explosive breccias have sharp contacts with the matrix. This fragmental matrix is composed of fine material, generally glass, in which fragmental crystals of plagioclase, hornblende, and augite are present. These crystals show no parallel arrangement as they do in the flow breccias. The matrix has the appearance of a crystal tuff or in some instances lithic tuff, if Pirrson's [32] nomenclature is used.

The explosive breccias were thrown from many different orifices throughout the volcanic field and came to rest in their present positions as rain-like falls of heavy materials. They represent Vulcanian explosions which threw forth not only volcanic rocks but also a few fragments of Paleozoic and pre-Cambrian rocks. One of the most striking characteristics of this volcanic field is the total absence of bombs.

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[31] J. T. Rouse: *The volcanic rocks of the Valley area, Park County, Wyoming*, Am. Geophys. Union, 16th Ann. Meet., Tr. (1935) p. 278-279.

[32] L. V. Pirrson: *The microscopical character of volcanic tuffs*, Am. Jour. Sci., 4th ser., vol. 40 (1915) p. 191-211.

The agglomerates differ from the breccias in that their fragments are all rounded. Churning action in the vent before extrusion is the probable cause of this rounding. The agglomerates show an absence of bedding, and this distinguishes them from the volcanic conglomerates which also contain rounded fragments. The fragments in the agglomerates are generally large; the tuffaceous matrix is subordinate; and the areal distribution of the agglomerates is confined to small local areas.

Finer material was frequently erupted and settled as ash falls. These ash falls are now represented by crystal and lithic tuffs.

Flowage Processes.—In rather limited areas, near some of the centers of extrusion, true flow breccias are found. Some of these breccias show alignment of fragments parallel to the direction of flow and can, therefore, be classified in the field, but in all other cases classification is dependent on microscropic examination. In thin sections the groundmass of the flow breccia generally consists of glass containing small laths of plagioclase which always show alignment parallel to the direction of flow and likewise show flowage around the fragments of the breccia. Flow breccias are relatively scarce in this field and make up a small part of the volcanic series.

Much of the pyroclastic material was dispersed by mud flows. Anderson [33] has pointed out the importance of mud flows as a mode of emplacement of volcanic breccias in the Tuscan formation of northern California. In the Absaroka Volcanic Field, conditions were very favorable for the development of mud flows. The relief of the pre-volcanic surface afforded ample slopes. Also, erosional intervals separate many of the early units so that relief was undoubtedly maintained throughout part of the volcanic period. The vast expanses of water-laid tuffs and volcanic conglomerates predicate ample moisture for the lubrication of these flows. Additional evidence is found in the fossil flora whose plants required moist conditions for growth.

In those areas where the mud flows were active the blocks in the breccias are frequently of abnormal size. In the cliffs along the South Fork of the Shoshone River in the vicinity of Valley, Wyoming, a heterogeneous mixture of rounded and angular fragments of volcanic rocks, averaging 8 to 10 feet in diameter but with some fully 150 feet in diameter, are held together by a tuffaceous matrix. This matrix shows bedding greatly contorted by plastic flow. These breccias rest on a surface into which very narrow valleys, 400 to 500 feet deep, had been cut prior to the breccia emplacement. In some other localities, however, the slope of the surface over which the mud flows moved is not so great as that just mentioned.

[33] C. A. Anderson: *The Tuscan formation of northern California*, Univ. Calif., Publ., Dept. Geol. Sci., Bull., vol. 23 (1933) p. 215-276.

But mud flows, as shown by Anderson,[24] do not require a steep slope for movement. To mud flows may be attributed the transportation of large blocks, especially of limestones, which are so often found in the breccias.

Water-laid Volcanic Rocks.—Running water as an agent for distributing the pyroclastics over wide areas is not emphasized in previous publications on the Absaroka region, yet throughout the entire field water-laid deposits prevail.

The volcanic conglomerates make up a large part of the pyroclastic series. They indicate cessations in volcanic outbursts followed by vigorous stream action. All the volcanic conglomerates are well bedded and abound in beautifully rounded pebbles, cobbles, and boulders.

Many of the tuff beds are water-laid; these can generally be recognized by the rounded grains and cross-bedding. Some of the tuffs represent ash falls in small, temporary lakes.

XENOLITHS IN THE PYROCLASTICS AND THEIR ORIGIN

The xenoliths in the pyroclastics are the fragments of Paleozoic sedimentary and pre-Cambrian igneous and metamorphic rocks that were torn from their surroundings by the volcanic outbursts. They are truly foreign to the pyroclastics and are far more abundant in the early acid breccias than in the early basic breccias. They are not very conspicuous in either the late acid or the late basic breccias.

The xenoliths in the early acid and basic breccias are of the same rock type as the basement formations in the region where they are found. These relations are shown in Table 6. None of the xenoliths shows any important alteration. Occasionally a limestone fragment is found that is partially recrystallized or slightly silicified around the edges.

GENERAL SUMMARY

At the beginning of the volcanic period the surface was quite rugged. There were hundreds of small vents as well as some large volcanoes, none of which built unusually high cones. After reaching the surface the pyroclastics were distributed widely by explosive processes, by mud flow, and by streams. That practically all the volcanic fragments reaching the surface were solid is evidenced by the lack of bombs or other phenomena which would indicate subaerial cooling and solidification. The distributing agents, together with the nature of the topography, determined the thicknesses of the various units.

[24] *Op. cit.*, p. 259.

ORIGIN OF THE EARLY BASALT SHEETS

The lava flows have issued through fissures because they are remarkably uniform in thickness over very wide areas. Variations in thickness in a distance of 40 or 50 miles are restricted to a few hundred feet which is not enough in a thousand-foot lava series to indicate emission from a central source. Many of the basalt dikes, which have the same composition as the lavas, are thought to represent the feeders. Active fissure eruptions seem to have been confined to the Absaroka field, as is evidenced by the absence of the early basalt sheets in the Shoshone Mountains to the southeast. The pyroclastics are, however, present in these mountains.

TABLE 6.—*Distribution, size, and character of some xenoliths in the Absaroka Volcanics*

Location	Character of Xenoliths	Average size of Xenoliths	Volcanic Unit	Basement Rocks*
Junction of Timber and Closed creeks, Crandall Quadrangle.	Dominantly Paleozoic limestone; some pre-Cambrian granite.	1 inch	Early Acid Breccia	Breccia rests on Madison limestone. A contact is visible.
Montana - Wyoming State line. North entrance to Yellowstone National Park.	Dominantly mica schists. Some ultrabasic rocks. All pre-Cambrian.	4–5 inches	Early Acid Breccia	Pre-Cambrian gneisses and schists. Contact not visible but immediately north of Gardiner River pre-Cambrian rocks outcrop over large areas.
Republic Mountain Cooke City, Montana.	Paleozoic limestone; pre-Cambrian granite.	2–7 inches	Early Acid and Early Basic Breccia	Paleozoic limestones. Contact visible.
South of Sunlight Basin, Crandall Creek.	Paleozoic limestone; pre-Cambrian gneisses and schists.	6–12 inches	Early Basic Breccia	Madison limestone. Contact visible.
Junction of Lamar and Yellowstone rivers, Yellowstone Park.	Pre-Cambrian granites and gneisses.	6–10 inches (some 3 ft.)	Early Basic Breccia	Pre-Cambrian gneisses and schists. Contact not visible. Pre-Cambrian rocks outcrop 2 miles to the north.
Jim Mountain-North Fork of Shoshone	Pre-Cambrian granites and quartzites.	3 feet	Early Basic Breccia	Wasatch. Contact visible.

* By Basement Rocks is meant the rocks on which the volcanics rest at a given locality. If the actual contact between the volcanics and the lower rocks is visible it is indicated in this column.

STRUCTURAL FEATURES

MAJOR STRUCTURES AT PERIPHERIES OF THE VOLCANIC FIELD

Numerous complicated structures are present in the Paleozoic and Mesozoic rocks along the eastern borders of the Absaroka field, many of which have been described.[35] Some of the thrust faults and folds are buried beneath the volcanics. The Heart Mountain, Logan Mountain, and Sheep Mountain overthrusts, and the folding and faulting in the Mesozoic rocks along the lower South Fork may be related to volcanic activity. Before suggesting any such relations for the major structures the smaller structures within the Absaroka Volcanic Field will be described.

DEFORMATION OF BASEMENT ROCKS CONTEMPORANEOUS WITH EXTRUSION OF THE VOLCANIC ROCKS

Upturning of Beds.—Along the northern and northeastern borders of the field the volcanics bury a surface of great relief which was developed on Paleozoic limestones before the volcanic cycle was inaugurated. On the north side of Republic Mountain, at Cooke City, Montana, a rather unusual structure was noted in the Bighorn limestone where it is in contact with the overlying early acid breccias (Fig. 7). The north face of this mountain shows relatively undisturbed, essentially horizontal, Paleozoic formations overlain unconformably by volcanics. The youngest Paleozoic formations occur at the east, but toward the west they were removed by pre-volcanic erosion and this face of the mountain shows an old valley side in cross-section with the volcanics resting on successively older formations toward the west. The contact between the sediments and the breccias is regular excepting in the sole case of the Bighorn limestone which here is sharply flexed as shown in Figure 7. This is the only formation that has been deformed and was probably caused by the pressure of the flow breccia against the Bighorn. No other hypothesis seems tenable as neither the beds to the east nor the underlying Gallatin have been disturbed. The flow breccias, probably extruded in the nearby

[35] W. H. Bucher, W. T. Thom, Jr., and R. T. Chamberlin: *Geologic problems of the Beartooth-Bighorn Region*, Geol. Soc. Am., Bull., vol. 45 (1934) p. 167-188.

W. H. Bucher: *Remarkable local folding, possibly due to gravity, bearing on the Heart Mountain Thrust problem*, Geol. Soc. Am., Pr. 1935 (1936) p. 69; *Volcanic explosions and overthrusts*, Am. Geophys. Union, 14th Ann. Meet., Tr. (1933) p. 238-242.

C. L. Dake: *The Heart Mountain overthrust and associated structures, Park County, Wyoming*, Jour. Geol., vol. 26 (1918) p. 45-55.

C. J. Hares: *Relative age of the Heart Mountain overthrust and the Yellowstone Park volcanic series*, Geol. Soc. Am., Pr. 1933 (1934) p. 84-85.

D. F. Hewett: *The Heart Mountain overthrust, Wyoming*, Jour. Geol., vol. 38 (1930) p. 536-557.

G. D. Johnson: *Geology of the mountain uplift transected by the Shoshone Canyon, Wyoming*, Jour. Geol., vol. 42 (1934) p. 809-838.

R. A. Laurence and M. M. Sheets: *Geology of Logan Mountain, Wyoming, and its bearing upon the Heart Mountain overthrust*, Geol. Soc. Am., Pr. 1933 (1934) p. 93-94.

M. M. Sheets: *Structural detail near the western border of the thrust sheets north of Shoshone River, Wyoming*, Am. Jour. Sci., 5th ser., vol. 29 (1935) p. 144-150.

vicinity, moved against the valley side just described and the layer of Bighorn was deformed. The flow was not sufficiently strong to tear this piece of Bighorn loose and incorporate it as an exotic block. Such movement was, no doubt, impeded by the steep escarpment of Madison, Three

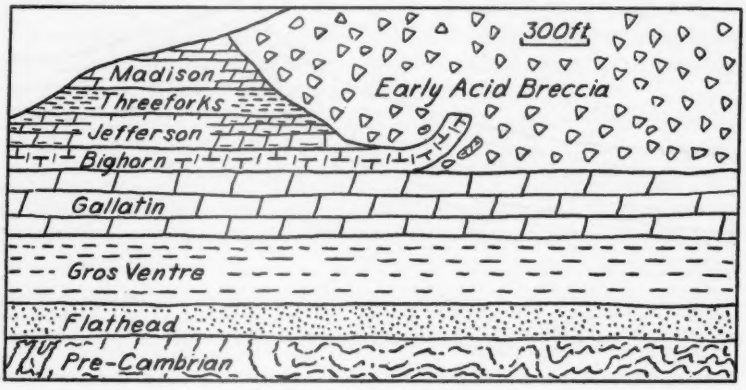

FIGURE 7.—*Breccia-limestone contact on the north face of Republic Mountain* Cooke City, Montana. The net vertical upturning of the Bighorn limestone is 300 feet.

Forks, and Jefferson limestone to the east. Small pieces of limestone (one foot in diameter) present in the breccia show alignment parallel to the direction of flow (east) of the breccia.

Minor Faulting.—In the valley sides of Crandall Creek, a tributary of the Clark Fork, a peculiar type of faulting may be seen, 1½ miles above the ranger station. The amount of throw of this fault, striking N. 60° W., is small, but the crowding and dragging of the beds is noticeable (Fig. 8). The formations affected are the Gallatin (upper Cambrian) and the upper shales of the Flathead (Cambrian); the lower Flathead limestone beds and overlying early basic breccias are undisturbed. Beneath the tilted Gallatin limestone the incompetent shales on the southwest side of the fault show well-developed drag folds which indicate movement from the southwest to the northeast (Fig. 8). The dip of the limestones away from the fault plane varies between 50 and 90 degrees, the steeper dips being on the southwest side. This zone of drag folding and faulting is approximately 300 feet wide, and on either side of the fault the beds rapidly return to a nearly horizontal position. (Here the Paleozoic formations have a regional dip to the southwest.)

Outcrops of the Paleozoic formations terminate one mile upstream (southwest) from the fault, and their dip is not sufficient to carry them

below stream level in this distance. The termination is due undoubtedly to pre-volcanic erosion and a steep, cliff-like valley wall faced southwest against which the early basic breccias accumulated. The volcanics, extruded to the southwest, moved against this cliff and applied pressure

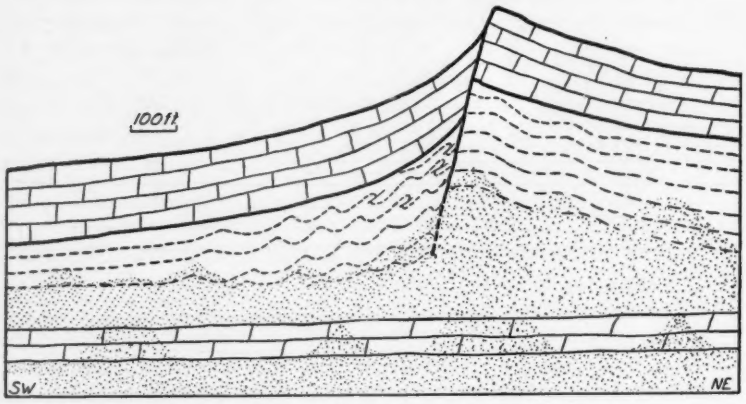

FIGURE 8.—*Minor faulting and drag folding on the northwest side of Crandall Creek*

One and a half miles west of the Crandall Ranger Station. The drag folds produced by pressure from the southwest are in the shale members of the Flathead, and beneath these shales the limestone beds are undisturbed. In this field sketch the top limestone is Gallatin and the stippled areas indicate outcrops obscured by talus. The throw of the fault is only 150 feet.

which found relief in horizontal crowding of some of the beds giving rise to this fault. Such an explanation would account for the movement and disturbance of higher beds while the lower beds remain undisturbed.

Limestone Blocks.—In certain parts of the Absaroka Volcanic Field the early basic breccias contain unusually large blocks of limestone which merit special consideration (Pl. 3, fig. 1). The best exposures of these limestone blocks are at the western end of the Sheep Mountain thrust mass between the North and South forks of the Shoshone River. Some of the blocks are as large as 500 feet in diameter and several hundred feet thick. Similar blocks are found on the north side of the North Fork of the Shoshone River, in the vicinity of Chalk and Logan mountains; southeast of the South Fork, near Carter Mountain; on the south side of Sunlight Creek in the Sunlight Basin; east of Lodge Pole Creek in the Crandall area; and in other isolated patches too numerous to mention.

Sheep Mountain (Pl. 3, fig. 2), composed of a large thrust mass of Paleozoic limestones resting on Mesozoic and Tertiary sediments, has been studied in detail by E. H. Stevens, and his manuscript is awaiting publication. His explanation for the presence of the limestone blocks in

the breccia follows. After thrusting, erosion of the thrust mass developed a surface of considerable relief. The topography may have been similar to that in the Garden of the Gods near Colorado Springs in Colorado, and remnants of limestone may have rested as umbrella rocks perched on weak sandstones and shales. Later, the invading volcanic breccias removed these remnants from their pedestals and incorporated them as foreign blocks in the breccia. In addition, the writer believes that many of the limestone blocks might have been torn loose from the thrust sheet as the breccias made their way to the surface.

Where they are surrounded by flow breccias the limestone blocks commonly show a thin coating of breccia. The limestone under such conditions has a thin border zone, several inches thick, of partial recrystallization or silicification resulting from slight metamorphism of its edges by the breccia, and in some instances very thin stringers of the flow breccia penetrate the limestone. Gouged, rounded, striated, or crudely polished limestone surfaces were developed occasionally as a result of turbulent flow of the viscous breccia. These surfaces should aid in determining the direction of movement of the breccias, but such a determination is handicapped by the complexity of the surfaces together with the fact that the smaller limestone blocks may have been disturbed many times by continual movement after their initial incorporation in the breccia. On Trout Creek the breccia coating on a large mass of limestone, probably a remnant of the thrust sheet, indicates that the breccias were moving eastward in this immediate vicinity.

In the Sunlight Basin area, on Mud and Beam creeks, large Paleozoic limestone blocks, varying between 20 and 100 feet in diameter and between 5 and 50 feet in thickness, are found imbedded in the early basic breccia. Here the breccia fills an old, pre-volcanic valley or depression, 3 or 4 miles wide, and the limestone blocks have been lifted 500 to 1000 feet vertically above the normal breccia-limestone contact. This lifting may have been produced by eruptions from the White Mountain Volcano located in this immediate vicinity.

In the vertical cliffs of Paleozoic formations and early basic breccia, on the south side of the Clark Fork River several miles east of Lodge Pole Creek, a large, steeply tilted block of Jefferson (Devonian) limestone rests on horizontal Gallatin (Cambrian). The block of Jefferson is 100 feet thick and was traced back into the mountain for 300 feet. It strikes N. 10° W. and the dip is 50° W. Near the base of this cliff and close to the contact between the inclined Jefferson and the horizontal Gallatin, the beds of the former are shot through with innumerable stringers of breccia. In the same region other blocks of Paleozoic limestone, 4 by 4 by 2 feet, are found in the nearly basic breccia. Here, again, is evidence

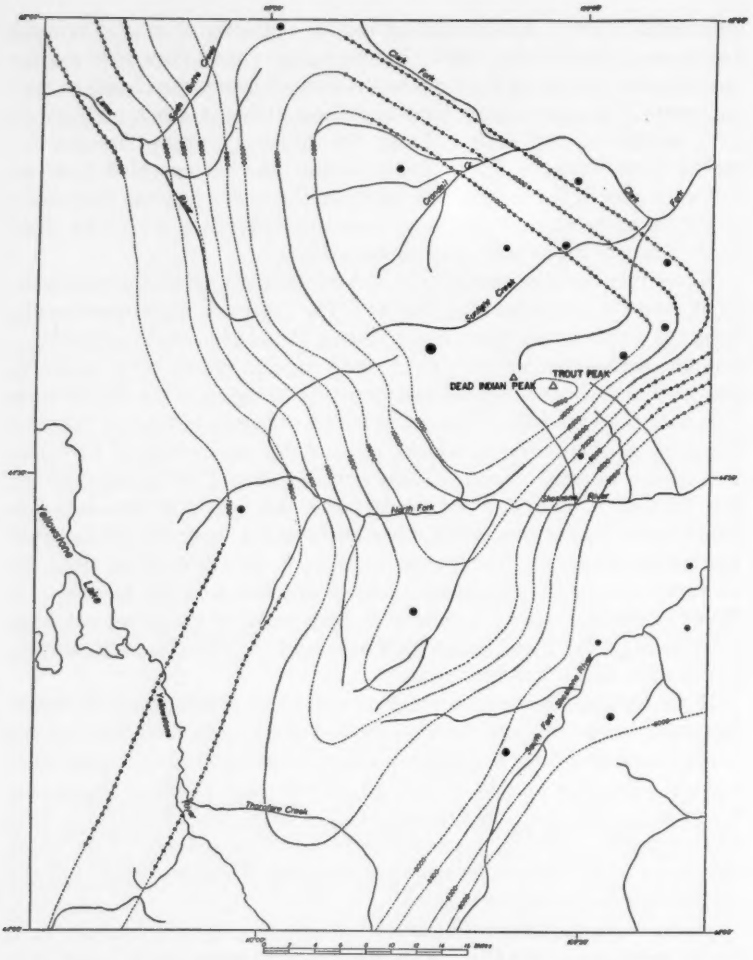

FIGURE 9.—*Structural contour map of part of the Absaroka Volcanic Field*

The 500-foot contours are drawn at the base of the early basalt sheets. Dashed lines indicate that the basalt sheets are present and the elevations are certain; dashed lines with cross bars indicate that the basalt sheets are absent but their former position is quite certain; dashed lines with circles indicate that the base of the basalts has been inferred. Solid black circles represent locations of some of the volcanic vents.

of strong pressures exerted by the volcanics at the time of extrusion. In this particular case a slab of Jefferson limestone was picked up and tilted as the breccias flowed over a rugged surface.

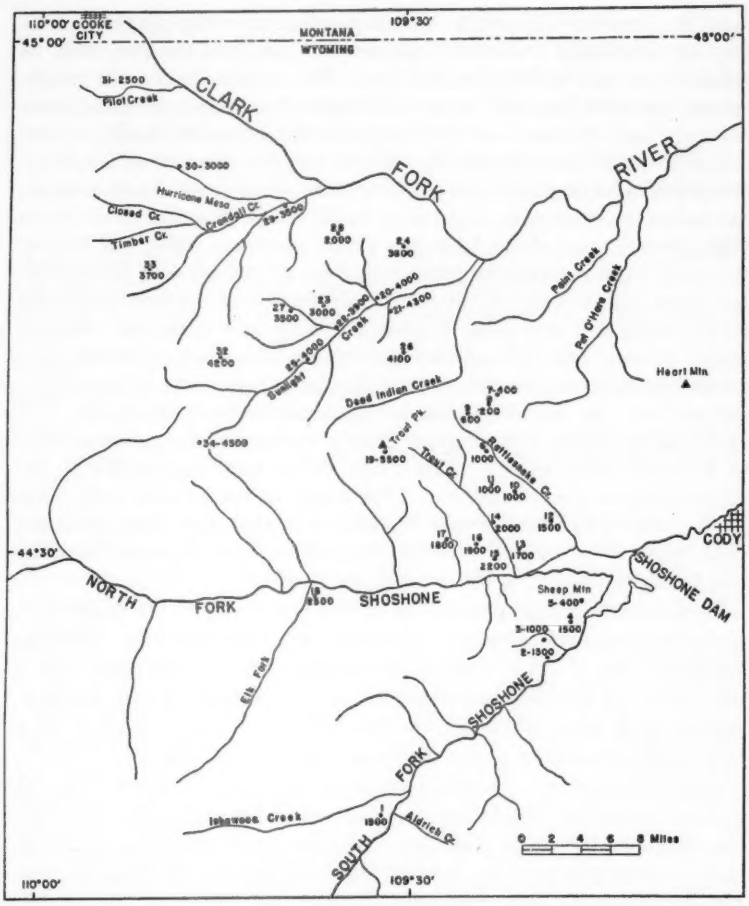

FIGURE 10.—*Map showing variations in thickness of the early basic breccia in the Absaroka Volcanic Field*

The first number is a location number and refers to the corresponding numbers in Table 7; the second number is the thickness of the breccia. Table 7 shows, in addition to thicknesses, the present elevations of the base of the breccias and the formations on which they rest.

DEFORMATION OF THE VOLCANIC ROCKS

Early Deformation.—It has been shown already (Table 5) that erosion and deformation occurred after the accumulation of a few of the individual volcanic units. Up Aldrich Creek, southeast of the Cody-South Fork road, the early basic breccias and the underlying Wasatch beds show a pronounced anticline trending northeast-southwest. On its southeast

flank the breccias dip steeply southeast, whereas on the northwest side they are essentially vertical. Exposures are poor and the axis could be followed for only several hundred feet. But normal to the axis a continuous section is exposed for several thousand feet. All the beds above the early basic breccias have been eroded in this part of the valley so that it is difficult to date the folding. There are, however, examples of deformation occurring after the accumulation of the early basic breccias and before the outpouring of the early basalt sheets. Farther up the South Fork, several miles above Ishawooa Creek, the lower tuffaceous beds of the early basic breccias, together with some of the breccias themselves, are tilted and have dips as great as 35 degrees. Yet the overlying early basalt sheets and late basic breccias are in no way disturbed. Here is ample evidence that deformation and erosion took place before the first of the basalts were extruded, because the lavas here cover an essentially flat surface. In one of the small tributary-gulches of the South Fork in this same vicinity a small thrust fault is confined to the tuffaceous beds of the early basic breccia. This thrust strikes northeast-southwest and dips 20 degrees to the northwest. The length of the exposed fault plane in the vertical cliff face is only 75 feet. The anticline, tilted beds, and fault were all developed after the early basic breccias were deposited and before the basalt sheets covered the area.

Deformation of this age seems to be confined wholly to the South Fork Valley and was not observed in other parts of the volcanic field. It seems significant, too, that the strike of the small thrust fault parallels that of the axis of the anticline just described and of the larger gentle anticline, formed much later, into which the South Fork has cut a valley.[36] This later anticline is shown on the structural contour map (Fig. 9).

Late Deformation—Interpretation of the Structural Contour Map.—A study of either the Crandall or the Ishawooa geologic map will show that the elevation of the early basalt sheets is not everywhere the same, though their stratigraphic position, between the early and the late breccias, does remain the same. After carefully checking the elevations in the field a structural contour map was drawn using the base of the early basalt sheets as a datum plane (Fig. 9). The outstanding feature of this map is the structural high in the vicinity of Trout and Dead Indian peaks. As this structural high is in an area from which Heart Mountain and other thrust masses may have been dispersed eastward, it warrants careful analysis.

Before considering the origin of this doming of the basalt sheets several pertinent facts should be emphasized.

[36] J. T. Rouse: *The physiography and glacial geology of the Valley region, Park County, Wyoming*, Jour. Geol., vol. 42 (1934) p. 740.

1. The map portrays the domed base of the basalts.

2. The thickness of the early basalt sheets is not extremely variable. In the central domed area they are 1100 feet thick while other outcrops of the same basalt sheets within a radius of 20 to 30 miles to the west vary between 900 and 1200 feet in thickness.

3. The early basic breccias, on which the basalt sheets rest, reach their maximum thickness in the Absaroka field in a region essentially the same

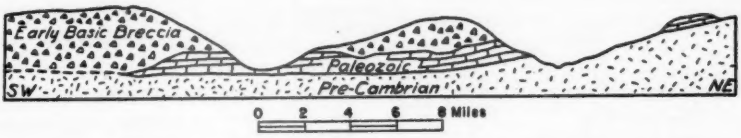

FIGURE 11.—*Generalized diagram showing the relation of the early basic breccia to the underlying Paleozoic sediments*

The Beartooth Mountains are at the northeast end of the sketch and the Sunlight Valley at the southwest. The breccias reach their greatest thickness at the southwest where the Paleozoic formations are absent.

as that occupied by the structural high (compare Figs. 9 and 10). Where the breccias show the maximum thickness of 5500 feet, the basalt sheets have an elevation of 11,000 feet, whereas circumferentially they are much thinner (1500 feet) and the basalts are at correspondingly lower elevations.

4. The majority of the Paleozoic formations have been removed in those areas where the thickness of the early basic breccia exceeds 4000 feet. This peculiar relation can best be explained by a diagram, Figure 11. This depression resulted from the removal of the Paleozoic formations prior to the accumulation of the breccia and extends along the upper part of Sunlight Creek and northeast of this creek to the vicinity of Trout Peak. The rather abrupt termination of these Paleozoic formations can be seen in many exposures in the Sunlight area. Erosion on such a scale seems unwarranted on the down-dip side of a monocline. That the regional structure here is a monocline, with the Paleozoic formations dipping southwest away from the Beartooth Mountain uplift, is shown in Figure 11. More surprising yet: although the Paleozoic formations have been removed from this area, 20 miles south of it hills consisting of little-resistant Wasatch and Cody formations appear beneath the volcanics (see Table 7; locations 15, 16, 17, and 18).

As to the origin of the domed structure, either the structural high represents an originally domed surface, on which the basalt sheets were extruded through many fissures, or it is the result of doming which took place sometime after the outpouring of the early basalt sheets.

The second explanation is favored. If the structural high resulted

from doming, this should show in the underlying Paleozoic formations, but as the greatest dip of the dome does not exceed 6 degrees it would not be striking to the eye. The Paleozoic formations are, moreover, dipping

TABLE 7.—*Present elevations of the base of the early basic breccias, together with their thickness and the formations on which they rest (the figures being confined to the vicinity of the structural high).*

Location*	Elevation at base of Breccia (feet A.T.)	Thickness (feet)	Basal formation
1. Upper South Fork	6300	1500	Morrison
2. South Fork, Castle Rock	5600	1500	Wasatch
3. South Fork	7200	1000	Madison (thrust sheet)
4. Bear Creek	6400	1500	Wasatch
5. Sheep Mountain	7200	400	Madison (thrust sheet)
6. Rattlesnake Creek	7100	1000	Bighorn
7. Pat O'Hara Mountain	10000	400	Amsden
8. Headwaters of Rattlesnake Creek	9000	200	Madison
9. Headwaters of Rattlesnake Creek	9000	600	Madison
10. Logan Mountain	7900	1000	Madison (thrust sheet)
11. Chalk Mountain	7700	1000	Madison (thrust sheet)
12. Lower Rattlesnake Creek	6500	1500	Frontier
13. North Fork	6300	1700	Madison (thrust sheet)
14. Trout Creek	6200	2000	Madison (thrust sheet)
15. North Fork	6000	2200	Cody
16. North Fork	6400	1900	Wasatch and Cody
17. Four Bear Ranch	6900	1800	Wasatch
18. North Fork at Elk Creek	6500	2500	Wasatch
19. Trout Peak	6000 (?)	5500	?
20. Sunlight Ranch	7000	4000	Gros Ventre and Gallatin
21. Beena Creek	6800	4300	Bighorn
22. Mouth of Little Sunlight Creek	7100	3900	Jefferson
23. Sunlight Creek	8000	3000	Madison
24. Russell Creek	7200	3800	Jefferson
25. Strawberry Gulch	7000	4000	Madison
26. Elk Creek	7200	4100	Madison
27. Little Sunlight	7500	3500	Madison
28. Reef Creek	8500	2000	Three Forks
29. Crandall Creek	7200	4000	Jefferson
30. North Fork, Crandall Creek	8200	3000	Madison
31. Pilot Creek	8000	2500	Madison
32. Black Mountain	?	4200	?
33. Indian Peak	?	3700	?
34. Sunlight Peak	?	4500	?

* The numbers in the first column refer to the exact location on the map, Figure 10.

Thicknesses are the present ones as measured in continuous exposures. No attempt has been made to estimate how much of the breccias have been eroded since deposition. Question marks indicate that the base of the breccia is not exposed.

southwest from the Beartooth Mountains toward the high, and hence the reflection of any doming in the underlying beds would be a flattening of their dip. Such flattening actually has been observed in the Sunlight and adjoining valleys where the Paleozoic formations, rather than con-

tinuing their southwest dip, are essentially horizontal for several miles. Although this is not conclusive evidence in itself, it is certainly suggestive.

The fairly uniform thickness of the basalt sheets seems to indicate that they were extruded on an essentially flat surface. Also the details of stratification in the breccias point to the obliteration of the great topographic relief of the pre-volcanic surface and to the spreading of the breccias in such a way as to produce a fairly uniform plain surface.

These observations indicate that the present regional attitude of the early basalt sheets is due to deformation that occurred sometime after they covered the surface. The anticlinal valley of the South Fork also is indicative of post-basalt movement. The absence of bedding in the late acid and basic breccias overlying the basalts prevents more accurate dating of this movement.

Little can be said regarding the origin of the depression in which a greater thickness of early basic breccia accumulated, as its base is buried beneath hundreds of feet of volcanics. It may represent a structure similar to that of the Ries Basin in Germany.[37]

RELATION OF THE VOLCANIC SERIES TO THE MAJOR THRUST MASSES

The Sheep, Logan, and Chalk mountain thrust masses were all produced before the early basic breccias were extruded. The field evidence for this follows:

1. The breccia dike, containing fragments of Mesozoic rocks and cutting across the Paleozoic limestone thrust mass of Sheep Mountain, has been previously described as a feeder for the early basic breccias (Fig. 5). If the early basic breccias had been thrust eastward with the Paleozoic formations as postulated by Hares,[38] one would not expect to find the thrust sheet cut by a breccia dike containing fragments of the Mesozoic rocks which now underlie the thrust sheet.

2. The thrust sheets were eroded deeply before the early basic breccias were extruded (Pl. 3, fig. 2). Concerning the Logan Mountain area, Laurence and Sheets write:

> "An erosion surface of considerable relief was developed upon the overthrust block, being sufficiently deep, in several places, to expose the Cretaceous shales which underlie the thrust. Later this surface was largely covered by Tertiary volcanics."[39]

Stevens,[40] who has completed a study of the Sheep Mountain thrust mass, is of the same opinion.

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[37] A. Bentz: *Das Nordlinger Riesproblem und seine Deutungen*, Sitzber. Preuss. Geol. landesanstalt, Ht. 3 (1928) p. 85-86.

[38] C. J. Hares: *Relative age of the Heart Mountain overthrust and the Yellowstone Park volcanic series*, Geol. Soc. Am., Pr. 1933 (1934) p. 84-85.

[39] R. A. Laurence and M. M. Sheets: *Geology of Logan Mountain, Wyoming, and its bearing upon the Heart Mountain overthrust*, Geol. Soc. Am., Pr. 1933 (1934) p. 93-94.

[40] E. H. Stevens: *written communication.*

3. The early basic breccias overlap the formations of the thrust sheets in exactly the same manner as they do formations in their normal stratigraphic succession.

4. In one locality on Post Creek the breccia appears to underlie a part of the limestone thrust mass. Careful examination showed a coating of breccia on the limestone and that the breccia accumulated against and filled in a re-entrant in the mass.

On Heart Mountain no volcanic rocks were found, but on McCulloch Peak a small patch of loose, angular volcanic fragments was observed. As these fragments are not rounded like those found in the recent gravels they may indicate former extensions of the volcanic series to this peak.

In a recent abstract, Stow states that the Wasatch beds contain hornblende derived from the early acid breccias, and as the Heart Mountain thrust mass rests on Wasatch it must have developed subsequent to the accumulation of the early acid breccia.[41] This does not offer, however, any objection to the previous statement that the thrusting took place before the early basic breccias were erupted, as a marked erosional unconformity separates the older early acid breccias from the younger early basic breccias.

If all the thrust sheets of this region, such as Heart Mountain, Sheep Mountain, and McCulloch Peak, reached their present position at the same time then this work of Stow, together with that of the writer, definitely dates the thrusting as occurring between early acid breccia and early basic breccia time (Eocene).

The discussion of the origin of the Heart Mountain and other thrusts together with that of the "gravity folding" on the South Fork will be given by Bucher and others in a later paper. The writer has attempted to show the relations of the volcanic series to these structures and the forces at work during the volcanic cycle. The type of deformation the breccias produced as they moved over the basement rocks, the moving of larger fragments by the breccias, and the folding and faulting developed in some of the volcanic units are all types of deformation of no great magnitude. If, however, these processes could be assumed to have operated on a much greater scale than may seem warranted they may help to account for the unusual thrusting in the regions adjacent to the volcanic field. Even on the smaller scale allowed for, volcanic activity in the Absaroka field must have been stupendous and of a magnitude far greater than that exhibited by present-day eruptions.

In any case, because of the magnitude of the volcanic activity and the peculiar aspect of the thrust sheets and folds adjacent to the Absaroka

[41] M. H. Stow: *Heavy mineral studies of Cretaceous-Eocene beds in the Bighorn Basin Region* [abstract], Geol. Soc. Am., Pr. 1936 (1937) p. 107.

field the writer feels that previously advanced hypotheses suggesting[42] that these structures originated by forces other than orogenic ones, whether they be volcanic explosions or large landslides, should be considered as working hypotheses rather than outrageous ones.[43]

SUMMARY AND CONCLUSIONS

The pyroclastic rocks and lava flows of the Absaroka Volcanic Field occur in two groups, each of which is made up of a lower acid breccia, a middle basic breccia, and an upper series of basalt sheets. The maximum thickness of the series in continuous exposure is 6500 feet, but the total composite thickness in a columnar section exceeds 11,000 feet. All the volcanic rocks are believed to have accumulated in the Eocene epoch. The old land surface on which the volcanic rocks were deposited was rugged with relief varying between 1000 and 4000 feet.

The pyroclastic types were erupted through hundreds of small vents and a few volcanoes of moderate size, their areal distribution being dependent on the methods of accumulation and the pre-volcanic topography. The basalt sheets are all fissure eruptions.

Some slight deformation of the basement rocks took place contemporaneously with the extrusion of the volcanic rocks. The volcanic cycle was interrupted locally by minor folding and faulting occurring immediately after the accumulation of the early basic breccia. Later deformation is reflected in the regional doming of the early basalt sheets, the highest part of the dome being in the vicinity of Trout and Dead Indian peaks. As this structural high is in an area from which Heart Mountain and other thrust masses may have been dispersed eastward, it may have an important bearing on the Heart Mountain problem.

The thrust sheets adjacent to the Absaroka Volcanic Field, such as Heart Mountain, Sheep Mountain, and McCulloch Peak, reached their present positions after the early acid but before the early basic breccias were deposited.

[42] W. H. Bucher: *Volcanic explosions and overthrusts*, Am. Geophys. Union, 14th Ann. Meet., Tr. (1933) p. 238-242.

J. T. Rouse: *Structural types associated with the Absaroka volcanics* [abstract], Geol. Soc. Am., Pr. 1935 (1936) p. 100.

[43] W. M. Davis: *The value of outrageous geological hypotheses*, Science, n. s., vol. 13 (1926) p. 463-468.

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NOTES ON A CORE-SAMPLE FROM THE ATLANTIC OCEAN BOTTOM SOUTHEAST OF NEW YORK CITY

BY J. A. CUSHMAN, L. G. HENBEST, AND K. E. LOHMAN

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INTRODUCTION

In 1935, C. S. Piggot,[1] while testing his core-sampling instrument along the continental shelf off the Middle Atlantic States, made a trial beyond the 1000-fathom line in the edge of the deep ocean basin. The first effort was successful in two respects. First, the capability of the machine to operate in deep water was demonstrated. Second, the core-sample proved, as anticipated, to be very interesting, because few if any core samples of present-day deep-sea bottom deeper than 2 to 3 feet had previously been obtained and consequently the understanding of submarine stratigraphy in existing oceans has been largely a matter of conjecture and inference.

The information supplied by the diatoms, foraminifers, and sediments in the core is so intimately related to studies now actively being pursued on the geomorphology of continental shelves that the writers believe it worth while to make the information more generally available without waiting to compare the results with information gained by study of cores collected the following year across the North Atlantic.

LOCATION AND DEPTH

The core was collected in 1935 by C. S. Piggot and Henry C. Stetson aboard the ship *Atlantis* of the Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, from the Atlantic Ocean at 39°13′ N. latitude, 72° W. longitude (about 150 land miles (240 kilometers) south of

[1] C. S. Piggot: *Apparatus to secure core samples from the ocean-bottom*, Geol. Soc. Am., Bull., vol. 47 (1936) p. 675-684.

New London, Connecticut, and 130 miles (210 kilometers) east of Atlantic City, New Jersey). The depth below sea level was calculated to be about 1200 fathoms or 7200 feet (2200 meters).

According to the United States Coast and Geodetic Survey (Pl. 1) the location is southeast of the pair of shallow indentations in the 1000-fathom contour representing the mouth of the submarine Hudson River gorge. The location belongs more to the deep oceanic floor than to the steep continental slope although it is only about 5 miles (8 kilometers) from the lower edge of the shelf.

METHOD OF PREPARING THE SAMPLE

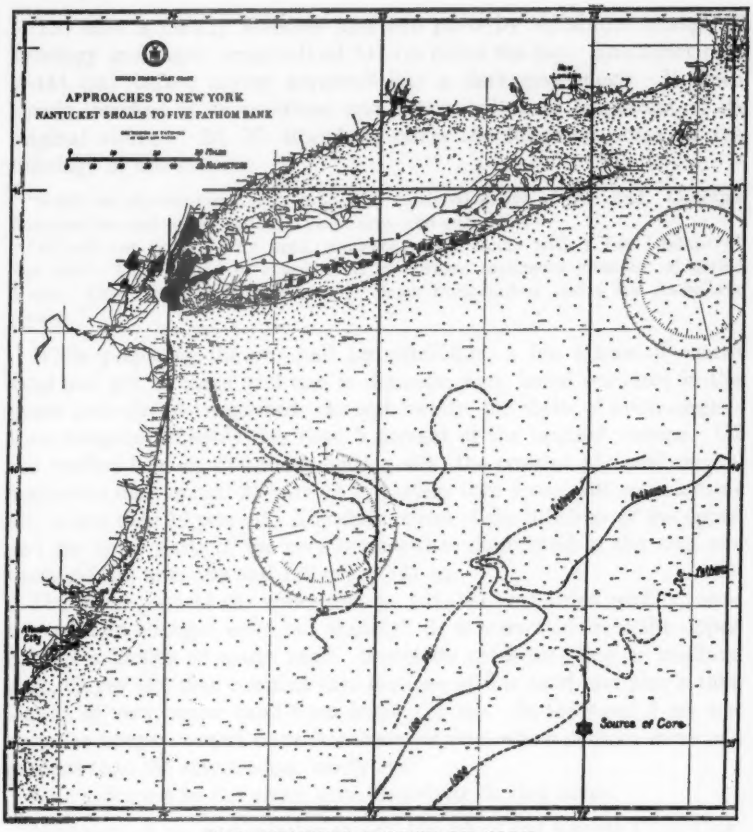
The core when presented to the United States National Museum had already received preliminary preparation for study under the supervision of Piggot at the Geophysical Laboratory, Carnegie Institution, Washington, D. C. When hoisted aboard the *Atlantis*, the brass tube liner containing the core was sealed at both ends to avoid disturbance of the contents by shipment. After arrival in Washington, the core was removed by milling two parallel grooves about 6 millimeters apart along one side of the brass tube to a depth that left only a thin membrane of brass beneath each groove. These membranes were cut with a knife, the narrow strip laid aside, barrel carefully drained, and the core permitted to dry to firmness. The core and barrel were then placed in a wooden trough to avoid vibration and the whole was sawed longitudinally into equal parts with a metal-cutting band saw. The core thus split suffered but slight disturbance of the sedimentary structure.

At the United States National Museum the study and preparation of the core were placed in charge of L. G. Henbest, who prepared one half for permanent preservation. The other half was divided and distributed for study as follows: reserve, generally 1/4 to 1/3; M. N. Bramlette, sedimentary petrography; K. E. Lohman, diatoms; P. D. Trask, organic substances; J. A. Cushman and L. G. Henbest, foraminifers.

The half of the core used for study was allowed to dry thoroughly. Desiccation cracks divided the core, representing a half cylinder, into sections of various lengths. These sections were divided longitudinally with a hacksaw into three or more segments. The segments used for micropaleontological study were trimmed of extraneous matter to avoid contamination, and similar care attended the remaining preparatory work.

LITHOLOGY AND GENERAL CHARACTER OF THE CORE

The original length of the core was 162 cm; after drying, 144 cm, a decrease of 18 cm. The original diameter was 48 mm but shrank locally to 35 to 40 mm on drying.



MAP SHOWING SOURCE OF CORE

The core is clearly divisible into two parts by an abrupt change of lithology at a depth (original) of 131 cm below the top. The upper part 0–131 cm) before drying appeared like a dark-gray muck. It dried slowly, cracked at 14 positions, and contracted 65 to 75 percent of its original volume. M. N. Bramlette offers the following notes on the lithology of this section:

"0–102 cm depth.—Gray, silty mud with scattered grains of fine sand. Contains Foraminifera and a few diatoms, Radiolaria, and coccoliths.

"102–131 cm depth.—Silty mud, somewhat more sandy with a few laminae of fine sand. Thin lamina of coarse sand at bottom, maximum diameter of grains 2 mm. These are rounded and pitted. Some Foraminifera and a few Radiolaria present."

While preparing the one half for exhibition, a few grains of coarse sand and grit as large as 2 mm in diameter were found scattered in the upper part already described. Except locally, the shells of micro-organisms compose probably less than 5 percent of the original volume. Of the residue held by 200-mesh bolting silk, the content of fossil micro-organisms may exceed 25 percent in certain thin zones, but more generally is less than 10 percent. The distinctness of the lithology of the upper and the lower parts of the core is somewhat diminished in the zone extending from near 102 and 107 cm to 131 cm.

The lower part of the core (that is, 131–161 cm) dried readily, contracted, and changed color but slightly. It is separated from the upper part by a lamina of coarse sand. Bramlette notes that it is a "medium gray, clayey silt that contains thin laminae of fine sand and also a thin lamina of very coarse sand 6 cm below the top. In the basal 9 cm are irregular lumps of marl or very calcareous clay which contain more organisms than the surrounding, sandy silt."

With reference to the entire core, Bramlette further notes:

"Mineralogy of the sand is rather uniform throughout and suggests a derivation from rocks of a dominantly hornblende gneiss or hornblende granite character. Glauconite grains are scattered throughout but nowhere numerous.

"The core above 102 cm is a massive mudstone type with no apparent bedding. Below 102 cm there are thin laminae of fine sand at irregular intervals of a few centimeters, with the conspicuous thin laminae of coarse sand between 131 and 138 cm and the more generally sandy character in the lower part of the core. No fine lamination nor regularity of the laminae of sand is sufficiently apparent to suggest varves."

DIATOMS

The diatoms in the core represent a mixture of species now living in the surface waters in the same region and of some fossil species, possibly derived from the erosion of Miocene rocks on the mainland. Diatoms were not abundant in any part of the core, although they were distributed through all parts, with the maximum number in the upper 6 cm.

The following list of species indicates the distribution and abundance in the parts of the core containing diatoms in greatest amount. The species marked by an asterisk were also reported by Mann[2] from a dredging taken by the U. S. S. *Albatross* in latitude 38°56′ N. and longitude 72°11′30″ W. at a depth of 813 fathoms. The *Albatross* dredging yielded a diatom flora containing, in addition to the species characteristic of the region today, many fresh-water forms and several Miocene marine species presumably eroded from exposures of Miocene diatomaceous beds and carried into the sea by the Delaware River. The fresh-water species found in the *Albatross* dredging were probably brought into the basin by the Delaware River. No fresh-water species were found in the core, and no adequate explanation can be offered to explain their absence.

The relative abundance of the different species is indicated in the following list by the symbols, C = common, F = frequent, and R = rare.

Several extinct marine species occur which will be considered separately. Although these extinct species have previously been known only from Miocene or older rocks, no age significance can be attached to their occurrence in this core. As already mentioned, it appears most probable that they were redeposited from Miocene rocks exposed in the drainage area of rivers supplying material to the present basin.

Pyxilla gracilis was originally described and was previously known only from the "Oceanic Series" of probable Miocene age on the island of Barbadoes.

Pterotheca kittoniana was originally described from the Eocene of the island of Mors, Jutland. It also occurs in beds at Simbirsk, Russia, that have been considered Cretaceous, but it has not been reported previously from North America.

Brightwellia hyperborea was originally described by Grunow from a dredging made by the U. S. S. *Gettysburg* in latitude 34°25′ N. and longitude 69°42′ W. at a depth of 2924 fathoms. This dredging most probably included either reworked material or was made from a submarine exposure of Miocene rocks, as this genus, except for the original record and the present one, is now known only from the Miocene.

Stictodiscus gelidus was originally described by Mann[3] from a dredging made by the U. S. S. *Albatross* in latitude 54°47′ N. and longitude 179°8′ W. at a depth of 913 fathoms. As Hanna[4] has ably pointed out, this dredging most probably was made from a submarine exposure of Miocene rock, as 55 percent of the species identified in the material were

[2] Albert Mann: *List of Diatomaceae from a deep-sea dredging in the Atlantic Ocean off Delaware Bay by the U. S. Fish Commission Steamer Albatross*, U. S. Nat. Mus., Pr., vol. 16 (1893) p. 303-312.

[3] Albert Mann: *Report on the diatoms of the "Albatross" voyages in the Pacific Ocean 1888-1904*, U. S. Nat. Herb., Contr., vol. 10, pt. 5 (1907) p. 268, pl. 50, fig. 5.

[4] G. Dallas Hanna: *Fossil diatoms dredged from the Bering Sea*, San Diego Soc. Nat. Hist., Tr., vol. 5, no. 20 (1929) p. 287-296, pl. 34.

List and distribution of species in core

Fossil	Diatom collection no., U. S. G. S. 2733	2734	2735	2739	2742
	Depth in centimeters from top of core 0–6	15–20	27–30	117–119	153–157
**Melosira sulcata* (Ehrenberg) Kützing	C†	F	F	..	F
Melosira cf. *M. siberica* Schmidt	F	..	..	..	..
Melosira westii William Smith	F	..	..	..	F
Podosira stelliger (Bailey) Mann	F	R	..	R	..
**Stephanopyxis turris* (Greville) Ralfs	F	F	..	..	F
Coscinosira oestrupii Ostenfeld	R	..	..	..	..
Thalassiosira cf. *T. gravida* Cleve	R	R	..	..	..
**Cyclotella striata* (Kützing) Grunow	R	R	..	..	..
Cyclotella stylorum Brightwell	..	..	..	..	R
Pyxilla gracilis Tempère and Forti	..	..	..	..	R
Pterotheca kittoniana Grunow	R	..	..	..	..
Coscinodiscus argus Ehrenberg	..	..	..	..	F
**Coscinodiscus asteromphalus* Ehrenberg	..	..	..	..	R
Coscinodiscus cf. *C. apiculatus* Ehrenberg	..	..	..	..	R
Coscinodiscus curvatulus Brunow	..	R	..	..	..
Coscinodiscus cf. *C. denarius* Schmidt	R	..	..	..	..
**Coscinodiscus excentricus* Ehrenberg	F	R	..	..	R
Coscinodiscus excentricus fasciculatus Hustedt	R	..	..	..	..
**Coscinodiscus lineatus* Ehrenberg	..	..	..	..	R
Coscinodiscus oculus-iridis Ehrenberg	F	..	..	..	..
**Coscinodiscus radiatus* Ehrenberg	F	F	F	..	R
Brightwellia hyperborea Grunow	..	..	R	..	..
Stictodiscus gelidus Mann	R	..	R	..	..
**Actinoptychus undulatus* Ehrenberg	F	F	..	..	R
Actinocyclus curvatulus Janisch	..	R	..	..	..
Actinocyclus ehrenbergii Ralfs	R	..	..	..	..
**Actinocyclus ehrenbergii crassa* (W. Smith) Hustedt	..	..	..	..	R
Actinocyclus ehrenbergii tenellus (Brébisson) Hustedt	R	..	..	..	..
Rhizosolenia sp.	..	R	..	..	..
**Triceratium alternans* Bailey	F	..	..	..	..
Triceratium favus Ehrenberg	F	..	R	..	..
Triceratium reticulum Ehrenberg	F	R	..	..	..
**Biddulphia aurita* (Lyngbye) Brébisson and Godey	..	R	..	..	..
**Biddulphia tuomeyi* (Bailey) Roper	..	..	..	R	..
Hemiaulus polymorphus Grunow	..	..	..	..	F
**Hemidiscus cuneiformis* Wallich	R	..	R	R	..
**Rhaphoneis amphiceros* Ehrenberg	..	..	..	..	R
**Rhaphoneis surirella* Ehrenberg	R	..	..	..	..
Thalassionema nitzschioides Grunow	F	..	..	..	R
**Cocconeis scutellum* Ehrenberg	R	..	..	..	..
Diploneis weissflogii (Schmidt) Cleve	F	R	..	..	R
Navicula excavata Greville	..	..	R	..	..
Nitzschia constricta Ralfs	R	..	..	..	..
Nitzschia cf. *N. granulata* Grunow	..	..	..	..	R

* Reported by Mann.

† C = common; F = frequent; R = rare.

described originally, and are known only, from Tertiary fossil deposits. Lohman has found this species occurring abundantly in the "Santos shale member" of the lower part of the Temblor formation at its type locality in the Temblor Range, California. The Temblor formation as a whole has been considered to be middle Miocene in age, but recent work by R. M. Kleinpell [5] suggests that the "Santos shale member" may be lower

[5] *Oral communication.*

Miocene or Oligocene. It is particularly interesting to find this species in the deep core in the Atlantic Ocean.

The oldest diatom-bearing formation now known along the Atlantic Coastal Plain is the Calvert, of middle Miocene age. The diatom floras from the Calvert formation in New Jersey, Maryland, and Virginia and the upper part of the Temblor formation in California are strikingly similar, but the four extinct species already mentioned are known only from rocks older than the Calvert formation. None of the extinct species characteristic of the Calvert formation was found in this core. If the four species in question, all of which occurred rarely, represent reworking of older sediments, an indication is given that beds containing diatoms at least as old as lower Miocene were exposed somewhere along the Atlantic Coastal Plain in late Pleistocene or Recent times.

Most of the diatoms found in the core are pelagic forms and are characteristic of cool to cold waters.

The diatoms in this core are grouped into two more or less distinct floras, characteristic of the upper and lower portions. As the central portion of the core furnished fewer diatoms than the top or the bottom, it is not possible to locate precisely the position of the change in the diatom floras. On the assumption (for reasons already given) that the four extinct species were reworked, the distribution of the remaining 40 living species is as follows: 23 occur in the upper two-thirds of the core only, 8 occur in the lower one-third only, and 9 occur in both parts. The flora from the upper part of the core contains many species which are abundant in the Pleistocene rocks along the Atlantic Coastal Plain. The flora from the lower part of the core contains many species which occur more abundantly in upper Tertiary rocks than in living floras. The absence in any part of the core of extinct species characteristic of the Pliocene suggests strongly that the bottom of the core is no older than Pleistocene. The presence of species which, although represented in living floras, apparently reached their maximum development in upper Tertiary time, however, suggests that the core may represent a fairly large portion of the Pleistocene.

FORAMINIFERA

The foraminifers belong to two distinct assemblages which correspond to the lithological differences already noted. The upper part of the core contains a mixture of pelagic and bottom-dwelling forms, of which the pelagic are the most abundant. The lower part likewise contains a mixture of pelagic and bottom-dwellers, but the pelagic forms are less overwhelming in numbers.

The fauna of the upper part of the core, particularly within the first 15 cm, is composed of species which live normally in this region at the

present time, as shown by dredgings of the *Albatross*. Practically all these species are near the northern limits of their ranges along the Atlantic coast. For the most part they extend from this region southward along the Atlantic continental shelf, some of them going into somewhat deeper water off Cape Hatteras. They include no species which are characteristic of very cold waters. With the possible exception of one species of *Bulimina*, apparently none of the species in the upper part of the core is found in the lower portion.

The species in the following list are the more significant members of the bottom-dwelling assemblage in the upper section (0-131 cm) of the core. The listed data of geographic distribution in this general region are based almost entirely upon the *Albatross* dredgings.

Bulimina elegans D'Orbigny, var. *exilis* H. B. Brady, 250-1781 fathoms from 32°39′ N. to 42°47′ N.

Bulimina inflata Sequenza, 349-1735 fathoms from 35°9′ N. to 42°47′ N.

Bulimina aculeata D'Orbigny, 30-1582 fathoms from 11°33′ N. to 41°11′ N.

Bolivina subcanariensis Cushman, 58-1769 fathoms from 32°39′ N. to 41°11′ N.

Bolivina subspinescens Cushman, 56-1345 fathoms from 17°45′ N. to 39°46′ N.

Pyrgo serrata W. Bailey, 196-1050 fathoms from 28°44′ N. to 39°42′ N.

Uvigerina peregrina Cushman, 16-2369 fathoms from 28°38′ N. to 42°22′ N.

Associated with these species are numerous shells of the usual pelagic forms of this area, such as *Globigerina inflata, G. dubia, Globigerinoides conglobata, Orbulina universa, Globorotalia menardii, G. tumida,* and *G. truncatulinoides* which live in the Gulf Stream waters and are sifted down in great abundance, particularly in this area where the warm Gulf Stream meets the colder waters from the north.

The section between 102 to 107 cm and 131 cm while lithologically and faunally most closely related to the upper part of the core is actually less sharply separated from the basal part than is superficially apparent. The change upward from the basal part is somewhat gradational.

The Foraminifera in the basal part of the core from 148 to 164 cm are, as has already been noted, entirely unlike those of the upper (0-107 cm) portion. The section from 131 to 148 cm is nearly barren. The globigerinids belong to species, particularly *Globigerina pachyderma* Ehrenberg, which are known as bottom-living forms mostly confined to the Arctic and within the Arctic Circle. With them are species of *Cassidulina,*

Bulimina, Virgulina, Eponides, and *Elphidium* which are characteristic of the Arctic region and some of which are known to be living at the present time in that area. The records for these also seem to show that in general they are species of colder and usually shallower water than those now present in the area from which this core was obtained. This Arctic fauna is well-known and has a wide distribution in the Arctic and subarctic regions. From these data the conclusion seems warranted that the material in the bottom of the core represents a fauna of a cold environment, such as that now present within the Arctic Circle. *Elphidium* is most commonly a shallow-water form. It is commonly commensal with chlorophyll-bearing Alga which must live in the zone of blue-green light of sufficient intensity to produce photosynthesis. From the few really adequate measurements available it appears that only in exceptional conditions of clarity can sufficient light penetrate deeper than 100 meters. *Elphidium* has been found in deep water at various places around Pacific islands, but the damaged condition of the shells indicated transportation out of their normal habitat. Several records, however, in the Pacific Ocean in deeper than normal habitat for *Elphidium* are reported which cannot be explained on the available information.[6] Whether the specimens were indigenous or erratics or perhaps derived from submarine exposures of pre-Recent sediments that originated under a different environment are questions that introduce uncertainty into the significance of most collections obtained by dredgings of supposedly Recent sediments. These circumstances, accordingly, modify the reliability of *Elphidium* as an indicator of shallow-water conditions.

GASTROPOD SPECIMEN

A broken specimen of gastropod was found close to the top of the lower division, depth 131 cm to 131.5 cm, and was identified by Julia A. Gardner, of the United States Geological Survey, as *Acteocina* sp. Gardner states that this genus is represented by both shallow-water and deep-water species in the Cenozoic and Recent faunas.

CONCLUSIONS

Obviously, far-reaching conclusions can hardly be drawn from the sedimentary record afforded by a single core. Question may be raised as to (1) whether the coring apparatus was vertical when fired; (2) whether the locality struck may have been the scene of dumping from ice rafts or icebergs; (3) whether the latest sediments at or near the mouth of the submarine Hudson gorge are normal at other places of similar depth and relationship to the continental slope; (4) whether faunas and sediments were mixed by the coring apparatus as it drove into the bottom; and (5)

[6] For records consult J. A. Cushman: *A monograph of the Foraminifera of the North Pacific Ocean,* U. S. Nat. Mus., Bull. 71, pt. 4 (1914) p. 30-34.

whether the fauna in the lower part of the core may have been swept from near shore by currents not now active.

The first question does not affect the conclusions suggested by the core record except as to thickness of the sediments penetrated. According to Piggot, the firing apparatus is sensitive, requiring only the instant for the "gun" to fall a fraction of an inch when the coring tube touches bottom. The gun and coring tube are heavy and have so much less surface exposed in proportion to their weight than the surface of the line that the greater friction on the line should keep the apparatus aplomb until it strikes bottom. If the apparatus were drifting rapidly and the lower end encountered a viscous bottom gel or material of similar consistency, the apparatus could probably be tipped, but from information given by Piggot, it appears unlikely that such combination of circumstances existed.

The second question cannot be definitely answered on the record of one core, but other cores taken higher on the continental shelf along the Atlantic by Piggot and Stetson indicate that great variation in texture of sediment is the rule rather than the exception. Most of the larger fragments of quartz and crystalline rock are water-worn, and some are perfectly rounded. Likewise for question three, the sediments in the core at hand are not sufficiently different to excite suspicion.

Careful attention was given to the question of drag of the core barrel on the core and consequent mixing of micro-organisms and sediments. Surprisingly little drag was found. The zone of fractured specimens and bending of bedding planes generally extended inward about 3 to 5 mm; the zone of drag was generally limited to the outer 1 to 2 mm. In a few places a slight downward bending was traceable to about 10 mm inward. Lateral displacement may have occurred near the 131-cm position where the upper mucky clay lay against the resistant though uncemented sandy lower bed. On the whole, however, evidences of drag and displacement are so small that much credit is reflected on the design of the coring apparatus. In preparing the samples for micro-organisms, the zone of drag was trimmed off and discarded. Various other measures were also taken to avoid contamination. If more evidence were needed, the absence in the lower part of the core of all but a single species of foraminifers belonging to the upper part offers practically conclusive proof of absence of contamination.

Obviously a number of cores or other evidence will have to be assembled to decide finally whether shallow-water shells are generally or ever swept out by undertow or other currents of this region into deeper water. The following circumstances, however, are suggestive in this connection: Deep-water, bottom-dwelling foraminifers mixed with the shallow-water and pelagic species would be expected if the normally shallow-water forms are erratics, but the fauna contains no such mixture. The

presence of pelagic forms is not very significant in this connection, though their smaller number in the lower, apparently shallow-water part of the core, is only suggestive, not conclusive, of either shallow-water environment or sufficiently rapid deposition of other shells and detritus to lower their proportion, or of both conditions together.

The very fact that the foraminiferal fauna in the lower part of the core is uniformly of a kind that now lives in the Arctic and subarctic and does not now live in this region definitely rules out recent action of this kind if one assumes that this core sample accurately represents the fauna.

All the paleontological evidence discovered is in agreement that none of the material can be older than Miocene. The conflicting evidence offered by the occurrence of a few Miocene diatoms in what otherwise appear to be Recent and possibly Pleistocene floras is best explained, under the limitations set by a single core and from the strength, lightness, and minuteness of the diatom tests, as the result of a mixture of fossils with the indigenous flora. The foraminiferal assemblages are composed of Recent and Recent or Pleistocene forms and contain no distinctly Miocene and Pliocene species.

From the ecologic evidence offered by the Foraminifera it may be concluded with considerable confidence that the lower part of the core is of Pleistocene age, because cold-water conditions are inferred and shallower-water conditions to some degree at least are rather generally accepted as concomitant with periods of ice advance. This fauna, however, has little in common with the apparently temperate-water, Pleistocene fauna described by Cushman and Cole[7] from the Chesapeake Bay region, nor with any other fauna, Cenozoic or Pleistocene, in rocks outcropping along the Atlantic coast. This situation loses significance in view of the fact that the marine faunal, floral, and stratigraphic record of the Pleistocene is fragmentary, and one can only conclude that, if Pleistocene, the fauna in the base of the core and that from the Chesapeake Bay region lived in different climatic subdivisions of the epoch.

Perhaps the most generally interesting features of the core are those which indicate considerable changes in sea level and the presence of coarse sand and grit even in the upper part of the core. Apparently, accepted ideas of the rate and nature of sedimentation on sea-bottoms require drastic revision. One must admit that the rate of sedimentation exceeds expectations.

[7] J. A. Cushman and W. S. Cole: *Pleistocene Foraminifera from Maryland*, Cushman Lab. Foram. Research, Contr., vol. 6 (1930) p. 94-100, pl. 13.

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MINERAL COMPOSITION OF MISSISSIPPI RIVER SANDS

BY R. DANA RUSSELL

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INTRODUCTION

Plausible hypotheses often become established as generally accepted facts by the mere passage of time and the lack of a direct challenge. Geology has afforded, and still affords, numerous examples of this principle. The particular case to which the writer wishes to call attention is the hypothesis that certain minerals, particularly the pyroxenes, amphiboles, and feldspars, are rapidly eliminated during transportation, and hence, that their presence in sediments indicates proximity to source rocks. Conversely, from this hypothesis, their absence indicates (1) deep weathering of the source rocks, or (2) derivation from pre-existing sediments, or (3) transportation for a considerable distance from the source area. To

most students of sediments, a "considerable distance" apparently means, in this instance, only a few hundred miles.

The literature dealing with clastic sediments is so full of cases in which this hypothesis has been treated as accepted fact and used as a basis for the interpretation of some aspects of the history of a particular sediment, that a cataloguing of such publications would almost be equivalent to a list of all papers dealing with the interpretation of clastic sediments. As a demonstration of this fact, three well-known American geological journals were examined for the period 1931-1935 inclusive. Almost every paper in these journals dealing with the mineralogy and interpretation of clastic sediments contained a reference to this hypothesis in which its truth was either implicitly accepted or implied.[1] Moreover, most textbooks on sediments accept its essential truth.[2]

For some time the writer has been engaged in studies of sediments from the Mississippi River, based on a suite of more than 600 samples collected from the bed of the river between Cairo, Illinois, and the Gulf of Mexico, by representatives of the Mississippi River Commission.[3] The mineral composition of a selected group of these samples has been determined in some detail in order to secure data on the mineralogy of the bed load sediment transported by one of the world's largest streams, and on the possible existence of progressive changes in the mineral composition of the bed load and bed material.[4] This study has afforded definite evidence concerning the validity of the hypothesis mentioned.

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[1] George A. Thiel: *Sedimentary and petrographic analysis of the St. Peter sandstone*, Geol. Soc. Am., Bull., vol. 46 (1935) p. 608.

O. R. Grawe and J. S. Cullison: *A study of sandstone members of the Jefferson City and Cotter Formations at Rolla, Missouri*, Jour. Geol., vol. 39 (1931) p. 329.

Robert Roth: *Evidence indicating the limits of Triassic in Kansas, Oklahoma, and Texas*, Jour. Geol., vol. 40 (1932) p. 723.

Arthur Pentland: *The heavy minerals of the Franconia and Mazomanie sandstones, Wisconsin*, Jour. Sed. Petrol., vol. 1 (1931) p. 35, 36.

G. C. McCartney: *A petrographic study of the Chester sandstones of Indiana*, Jour. Sed. Petrol., vol. 1 (1931) p. 90.

Hans Becker: *A study of the heavy minerals of the pre-Cambrian and Paleozoic rocks of the Baraboo Range, Wisconsin*, Jour. Sed. Petrol., vol. 1 (1931) p. 94, 95.

Margaret D. Stearns: *The petrology of the Marshall Formation of Michigan*, Jour. Sed. Petrol., vol. 3 (1933) p. 109.

C. E. Needham: *The petrology of the Tombigbee sands of eastern Mississippi*, Jour. Sed. Petrol., vol. 4 (1934) p. 58.

[2] For example, P. G. H. Boswell: *On the mineralogy of sedimentary rocks*, Murby and Co., London (1933) p. 47, para. 2, and H. B. Milner: *Sedimentary petrography*, Murby and Co., London (1929) p. 438-451.

[3] Previously published results of these studies include: R. Dana Russell: *The size distribution of minerals in Mississippi River sands*, Jour. Sed. Petrol., vol. 6 (1936) p. 125-142, and R. Dana Russell and Ralph E. Taylor: *Roundness and shape of Mississippi River sands*, Jour. Geol., vol. 45 (1937) p. 225-267.

The mineral composition of samples from the principal tributaries of the Mississippi have also been studied and the results are being prepared for publication.

[4] The term "bed material" is used by the Mississippi River Commission to indicate sediment at rest (usually temporarily) upon the bed of the stream, in contrast to the bed load and suspended load, which are in motion. Sediment which is bed material at the time of sampling usually becomes bed load during periods when the stream possesses greater transporting ability.

The writer wishes to express his indebtedness to the Mississippi River Commission for furnishing the samples and for aiding the study financially. He is particularly indebted to Mr. Charles W. Schweizer, Engineer, Mississippi River Commission; Lt. Frank H. Falkner, Director, and Lt. Herbert D. Vogel, former Director, of the United States Waterways Experiment Station; and Mr. Spencer J. Buchanan, Associate Engineer in charge of the Soil Mechanics Laboratory of the Experiment Station; for their interest and helpful cooperation. He also wishes to express his appreciation to his colleagues in the School of Geology, Louisiana State University, for their valuable criticism and advice.

HYPOTHETICAL EFFECTS OF STREAM TRANSPORTATION UPON THE MINERAL COMPOSITION OF THE TRANSPORTED BED LOAD

GENERAL STATEMENT

The hypothetical effects of stream action upon the coarser material transported near the bed of the stream—i. e., the bed load—may be naturally divided into (1) the effects produced by abrasion and chemical weathering during transportation, and (2) those resulting from the sorting action of the stream. Although in some cases these may in part complement each other, in others they may tend toward results that are diametrically opposed. Therefore it will be well to consider them separately.

ABRASION AND WEATHERING

The fact that some minerals are softer than others, and some more brittle and more easily fractured, has been known since minerals were first noticed and studied by man. From that observation, a logical step led early geologists to the hypothesis that the softer and more brittle minerals are more rapidly destroyed during transportation. To this effect has been added the relatively greater loss of minerals more susceptible to the effects of chemical weathering, considering here only the weathering that may take place before the minerals are permanently deposited.

These two effects, abrasion and chemical weathering, have been considered to be largely supplementary,[5] for most of the minerals usually cited as being less able to withstand abrasion are also those most easily weathered. The feldspars, the pyroxenes, and the amphiboles, among the more common detrital minerals, are classed as particularly susceptible to abrasive action because of their brittle character and good cleavage. They are also more susceptible to alteration than most other common detrital minerals. Quartz, rutile, zircon, tourmaline, and others are, on the other hand, not only considered to be more resistant to abrasion but are also more resistant to the ordinary agents of chemical weathering.

[5] Actually, the coincidence between resistance to abrasion and resistance to alteration and solution is not so close as is often assumed. This is demonstrated later.

The hypothesis stated is logical and reasonable, for there is no doubt of the tendency of the more resistant minerals to outlast the less resistant. But many students of sediments have assumed that this tendency is so pronounced in its effects that certain minerals are unable to survive more than a short journey from their source area. That this belief is almost entirely an assumption can be readily ascertained by a survey of the literature, which, however, yields little concrete evidence. Abundant data show that in the older sediments the more resistant minerals usually preponderate, but this does not necessarily mean that the less resistant minerals have been eliminated during transportation. It may equally well result from the destruction of the less resistant minerals by chemical alteration after deposition of the sediment containing them. Attention, therefore, should be directed chiefly to present-day sediments, if accurate data on the relative resistance of minerals to transport are to be secured, and here one finds a notable scarcity of reliable information.

Mackie [6] is perhaps most responsible for the prevalence of this concept of rapid destruction during transportation, especially as concerns the feldspars. His results for sands from the Findhorn River show a decrease from 42 percent feldspar to 21 percent 30 to 40 miles downstream, and similar results for sands from the Spey River, both in Scotland. That is, half of the feldspar, according to Mackie, is destroyed in the course of only 30 or 40 miles of transportation. As Mackie's results are based on the analysis of only a few samples, they can hardly be judged conclusive, especially since the factor of variation in composition with differences in grain size and degree of sorting, recently shown to be of importance,[7] was not considered. Martens' study [8] of beach sands also showed a rather rapid decrease in the amount of feldspar, but the decrease was far from uniform and, as acknowledged by Martens, may in part be explained by variations in grain size of the samples analyzed. In contrast to these results are those of Pettijohn, and of Pettijohn and Ridge, on lake beach sands.[9] These investigators directed their attention chiefly to the heavy minerals, and, though they found progressive changes in the mineral composition of the sands, they ascribed them to selective sorting action by the transporting agent, rather than to abrasion or other factors. In some cases the results were exactly the reverse of hypothetical progressive changes resulting from abrasion or chemical weathering during transport.

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[6] William Mackie: *The sands and sandstones of eastern Moray*, Edinburgh Geol. Soc., Tr., vol. 7 (1893-1898; read March 19, 1896) p. 148-172.

[7] R. Dana Russell: *op. cit.* and included references.

[8] J. H. C. Martens: *Persistence of feldspar in beach sand*, Am. Mineral., vol. 16 (1931) p. 526-531.

[9] F. J. Pettijohn: *Petrography of the beach sands of southern Lake Michigan*, Jour. Geol., vol. 39 (1931) p. 432-455.

F. J. Pettijohn and J. D. Ridge: *A mineral variation series of beach sands from Cedar Point, Ohio*, Jour. Sed. Petrol., vol. 3 (1933) p. 92-94.

Sands collected from a spit on Lake Erie, for example, showed a progressive increase in the amount of hornblende, diopside, and hypersthene, in the direction of travel. Pettijohn and Ridge dealt with beach sands, however, hence their results probably are not directly applicable to stream sediments, where conditions of transportation and, perhaps, the rigor of abrasive action, differ from those of a beach. This paper is concerned chiefly with stream sediments.

In addition to Mackie's work, previously cited, many other studies of the mineralogy of stream sediments have been made, but most of these have dealt with the composition of a few isolated samples. Studies of a progressive series of samples are rare. One of the earliest, and one of the best, is that of Artini, on the sands of the Po and other Italian streams.[10] Artini was one of the first, if not the first, to use a series of numbers to represent relative abundance of the minerals in a sediment, a forerunner of the so-called Watt system, though Artini's system of numbering is the reverse of Watt's; 1 indicating very abundant, and 10, rare. Although Artini was considerably in advance of his contemporaries as regards quantitative results, his data are not sufficiently accurate to allow definite conclusions to be drawn. No marked progressive changes in the amounts of the minerals are evident from his data, however.

More recently, studies of stream sands have been made by Burri, Stow, and King.[11] Burri, studying samples from the Tessin River in Switzerland, found that in the 80 to 100 kilometers from the headwaters of the stream to its mouth in Lake Maggiore, the hornblende decreases from 44 percent of the heavy separate near the headwaters to about one at the mouth. This is not due to a loss by abrasion, however, but, according to Burri, to the fact that hornblende-bearing rocks only outcrop in one small area near the headwaters, and consequently the percentage of hornblende continually decreases as a result of "dilution" by material contributed by tributaries. The garnet, on the other hand, increases in percentage, by the addition of material from garnetiferous rocks, until the lower portion of the stream is reached, where it decreases somewhat, probably due to the absence of garnetiferous rocks in this portion of the stream's drainage basin.[12] Stow, in a preliminary study of some sediments from the James River in Virginia, concluded that most of the minerals added to the sediment persisted for "many miles" below their

[10] E. Artini: *Intorno alla composizione mineralogica della sabbie di alcuni fiumi del Veneto, con applicazioni etc.*, Riv. Min. Crist. Ital., Padova, vol. 19 (1898) p. 33-94.

[11] C. Burri: *Sediment petrographische Untersuchungen an alpinen Flüssanden. I, Die Sande des Tessin*, Schweiz. Min. Pet. Mitt., vol. 9 (1929) p. 205-240.

M. H. Stow: *A preliminary investigation of some sediments from James River, Virginia*, Am. Mineral., vol. 15 (1930) p. 528-533.

Byron F. King: *Mineral composition of sands from Monongahela, Allegheny, and Ohio Rivers*, Am. Mineral., vol. 17 (1932) p. 485-490.

[12] C. Burri: *op cit.*, p. 229-231.

source, but that limonite will not be transported any great distance from its source area.[13] King studied a few samples from the Monongahela, Allegheny, and Ohio Rivers, but gave no data on variations in mineral composition in the direction of transport. With the exception of five samples, percentages of the minerals were not determined, relative abundance being shown by the Watt method. Downstream changes are not evident in his data, but the lack of more accurate results prohibits definite conclusions.

Thus it appears that actual data concerning the relative resistance of minerals to abrasion and weathering during transportation by streams are rare and not sufficiently accurate to justify conclusions.

SORTING ACTION

The effects of sorting action by waves and currents upon the mechanical composition of sediments have been studied rather extensively, and the general outline of the picture is well known, though details remain to be filled in. Effects of sorting upon the mineral composition of sediments, however, have only recently received much attention. Mackie [14] discussed the general effects of sorting action upon the distribution of the heavy mineral group as a whole, and more recently a series of papers have emphasized the variations in mineral composition resulting from local differences in conditions of sedimentation.[15] Progressive sorting action may also produce progressive changes in mineral composition in the direction of transport. Such sorting may be on the basis of specific gravity (the heavier minerals being dropped sooner than the lighter ones), on the basis of shape, or on the basis of size. The first has been recognized as a possibility for some time, though quantitative data on the magnitude of this action are lacking. That sorting on the basis of the shape of the grains may produce progressive changes in mineral composition appears to have been demonstrated by Pettijohn, and Pettijohn and Ridge, with regard to beach sands.[16] According to Wadell,[17] in sediments which are transported chiefly by suspension, grains of low sphericity tend to outrun those of higher sphericity. Hence a sediment transported dominantly by suspension should show a progressive increase, in the direction of travel, in the amount of flaky or flat minerals—i. e., those which, due to cleavage or original shape, have a relatively low degree of sphericity. If, on the

[13] M. H. Stow: *op. cit.*, p. 531-533.

[14] William Mackie: *The principles that regulate the distribution of particles of heavy minerals in sedimentary rocks, as illustrated by the sandstones of the north-east of Scotland*, Edinburgh Geol. Soc., Tr., vol. 11 (1915-1924; read Jan. 21, 1920) p. 138-164.

[15] R. D. Russell: *op. cit.* and included references.

[16] F. J. Pettijohn: *op. cit.*
F. J. Pettijohn and J. D. Ridge: *op. cit.*

[17] H. Wadell: *Volume, shape, and roundness of rock particles*, Jour. Geol., vol. 40 (1932) p. 443-451.

other hand, the particles are moved dominantly by rolling, those possessing a higher degree of sphericity will outrun the others. As the feldspars, the pyroxenes, and the amphiboles have, in general, a lower degree of sphericity than quartz and the other "resistant" minerals, a sediment transported chiefly in suspension might show a progressive increase in the percentages of the less-resistant minerals in the direction of transport. This appears to be the case at the Cedar Point spit in Lake Erie [18] and is partially true also of the beach sands of southern Lake Michigan.[19] With regard to stream sands, no published data on this point are available.

Progressive sorting of sediments on the basis of size—i. e., progressive changes in average grain size—may also introduce progressive changes in mineral composition. Minerals which commonly occur as grains smaller than the average, like the accessory minerals of crystalline rocks, in addition to being more abundant in the finer portions of individual samples, make up a larger percentage of samples of smaller average grain size. It is obvious, therefore, that a progressive decrease in the grain size of a series of sediments introduces a factor tending toward an increase in the percentage of those minerals that are smaller than the average. The importance of this effect has not been determined, however.

Thus there appear to be several factors that may operate to produce progressive changes in the mineral composition of sediments, in addition to changes resulting from the introduction of new material. Some of these may tend to produce results opposed to those caused by one or more of the others. These factors are: (1) differential abrasion and weathering during transport, and (2) progressive sorting on the basis of specific gravity, shape, and size. In the study of sediments from the bed of the Mississippi, an attempt has been made to evaluate the effectiveness of each of these factors.

STUDY OF SEDIMENTS FROM THE BED OF THE MISSISSIPPI RIVER

COLLECTION AND TREATMENT OF THE SAMPLES

Nearly 1000 samples of bed material were collected by the Mississippi River Commission during 1932 and 1934. About two-thirds of these are from the Mississippi River between Cairo, Illinois, and the Gulf of Mexico. The remainder are from the Atchafalaya River, the upper Mississippi, and the principal streams tributary to the Mississippi. The sampler used consists of a "steel pipe 4 inches in inside diameter and 4 feet long, closed at one end, and flaring at the other end to a diameter of about 8 inches. The device is attached by means of a bail to a 1¼ inch rope, with which

[18] F. J. Pettijohn and J. D. Ridge: *op. cit.*
[19] F. J. Pettijohn: *op. cit.*

it is controlled from the boat." [20] After being filled by towing it downstream, it is "pulled in, the contents emptied by dropping the open end of the pipe on a board, and a sample of the material is placed in a properly marked can."

Mechanical analyses and absolute specific gravity determinations of the samples have been made by the Soil Mechanics Laboratory of the United States Waterways Experiment Station. These results have been published [21] for the samples from the lower Mississippi, the Atchafalaya, and a few samples from some of the tributaries (including all samples collected up to the end of May, 1934). Although most of the samples are of sand, they range, in average size of grain, from fairly coarse gravel to fine silt and clay. There is, moreover, a progressive downstream decrease in the average grain size. This progressive decrease in average size is by no means uniform, and it is not uncommon to find a sample of gravel succeeded by one of fine sand, or vice versa. The sorting of the samples is also highly variable, some being almost as poorly sorted as glacial tills, whereas others show as marked a concentration into a narrow range of sizes as the most highly sorted dune and beach sands. Although a detailed discussion of these features must be left for a later article, the effect of these variations on the mineral composition should be noted. As has been pointed out by several workers, variations in conditions of sedimentation that produce differences in average grain size and in degree of sorting also produce differences in mineral composition between samples and in the size distribution of the various minerals within a single sample.[22] A detailed study of seven samples from the Mississippi River showed that local variations in mineral composition, induced by local differences in conditions of sedimentation, were so great as to largely obscure any progressive downstream changes in mineral composition. Six of these samples consisted of three pairs in which the members of each pair differed from each other in average grain size or degree of sorting, or both, but were collected from adjacent points in the river, where there was little or no possibility of addition of material by tributaries or caving banks between the samples of a pair. A study of the results of these detailed analyses yielded a method of comparison that eliminates most of the differences in mineral composition resulting from variations in sorting and average grain size.[23] This method, which has been used in the present study, con-

[20] *Studies of river bed materials and their movement, with special reference to the lower Mississippi River*, U. S. Waterways Exper. Sta., Paper 17 (1935) p. 120.

[21] *Op. cit.*, p. 116-161.

[22] R. D. Russell: *op cit.*, and included references.

[23] *Ibid.*

sists in analyzing only the 100-mesh grade [24] for the "light" minerals and, for the "heavy" minerals (specific gravity greater than 2.85), averaging the composition of the 200-mesh grade with the composition of a grade midway between the grade containing the maximum amount of material and the finest grade.

As the analysis of all the samples collected would obviously require an excessive amount of time, samples for analysis were picked at intervals from Cairo to the Gulf. The first group analyzed consisted of samples at approximately 100-mile intervals, with additional samples above and below the mouths of important tributaries. This interval was subsequently reduced by the analysis of additional samples, so that the samples whose analyses are here reported were taken at 25-mile intervals from Cairo to Profit Island, Louisiana, where the last tributary enters the Mississippi, and at 10-mile intervals from Profit Island to the Gulf, with the exception of the stretch from Baton Rouge to New Orleans, where fewer samples were collected. The samples analyzed are listed in Table 1, the number of each sample indicating the mileage, by the river, below Cairo, Illinois, at the point where the sample was collected. The approximate location of the samples may be found by reference to the map (Fig. 1). All samples are from the talweg (channel), but some are from pools, some from crossings, and some from straight reaches of the river.

The procedure used in the analyses was as follows: The 100- and 200-mesh grades, as well as a third grade chosen by inspection of the mechanical analysis of the sample (as already outlined), were separated by sieving, using a Ro-tap shaker and standard wire-mesh sieves. The material in each grade was then weighed and the "heavy" minerals separated in bromoform, using glass funnels equipped with rubber tubes and pinchcocks. After washing and drying the light and heavy separates, the strongly magnetic materials (magnetite and flakes of iron) were separated from the heavy separates with a small horseshoe magnet, and the

[24] The designations and sizes of the grades used in this study are as follows:

Designation of grade	Sieve sizes (diameter of openings in mm.) Passed by	Retained on
14 mesh	10 mesh, 1.651	14 mesh, 1.168
20 mesh	14 mesh, 1.168	20 mesh, 0.833
28 mesh	20 mesh, 0.833	28 mesh, 0.589
35 mesh	28 mesh, 0.589	35 mesh, 0.417
48 mesh	35 mesh, 0.417	48 mesh, 0.295
65 mesh	48 mesh, 0.295	65 mesh, 0.208
100 mesh	65 mesh, 0.208	100 mesh, 0.147
150 mesh	100 mesh, 0.147	150 mesh, 0.104
200 mesh	150 mesh, 0.104	200 mesh, 0.074
<200 mesh	200 mesh, 0.074	pan.

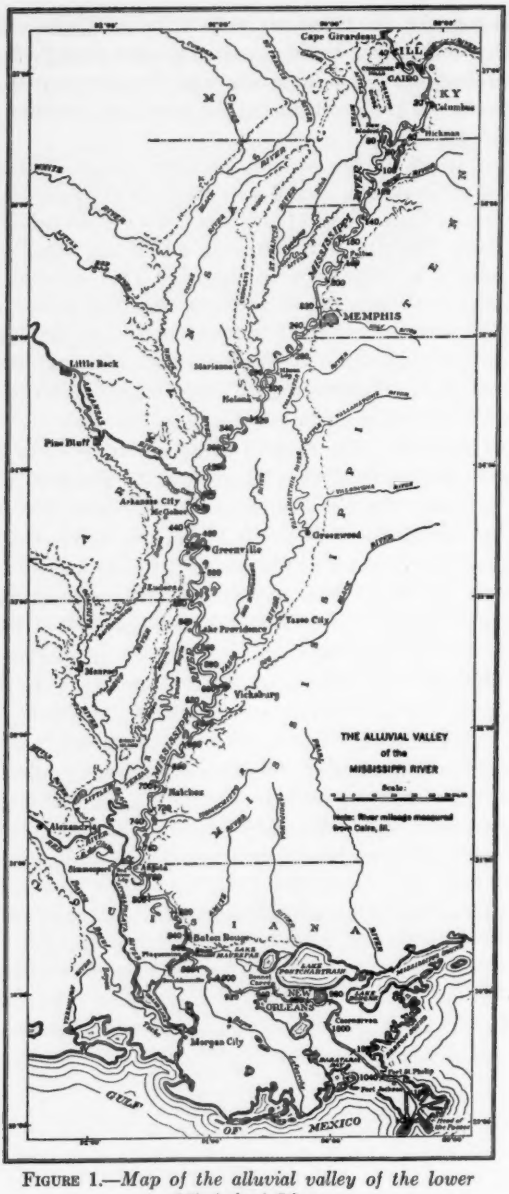


FIGURE 1.—*Map of the alluvial valley of the lower Mississippi River*

weight percentages of the total heavy separates and of their magnetic portions were calculated. A fraction of the 100-mesh grade large enough for two microscope slides was then separated with a "microsplit".[25] This fraction was split in half, one half stained with malachite green, and the other mounted in kollolith.[26] Another fraction was split out for examination in a liquid of refractive index 1.560, for the determination of plagioclase feldspars more calcic than andesine. This treatment of the light minerals, which has been previously described,[27] has been found to yield more accurate results than the usual methods in the determination of the percentages of quartz and the feldspars. The heavy separates (minus the strongly magnetic materials) from the other two grades were split down by the aid of the "microsplit" and mounted in piperine.[28] Frequency percentages of the minerals in each of the slides were determined by traversing the slides horizontally with the aid of a mechanical stage and counting the grains of each mineral as they passed the vertical cross-hair, care being taken, of course, that no grain be counted more than once. Between 300 and 600 grains were counted in each slide. The rest of the slide was then examined for minerals that may not have been present in the area covered by the count.

MINERAL COMPOSITION OF THE SAMPLES

GENERAL STATEMENT

The mineral composition of the samples is shown in Table 1. The results of the analyses of the light minerals are shown in the upper part of the table, and in the lower part are presented the data for the heavy minerals. The percentages of heavy minerals for most of the samples is an arithmetical average of the percentage of each mineral in two grades: the "midway" grade and the 200-mesh. In many of the samples, however, particularly in the lower part of the river, the 200-mesh grade was also the "midway" grade, and hence was the only one analyzed for heavy mineral content. Percentages are shown only to the nearest whole percent, because figures carried beyond the decimal give an impression of greater accuracy than is inherent in the method of analysis used.[29] The figures for the total percentages of the pyroxenes, amphiboles, garnets, and the non-metallic accessory minerals of crystalline rocks were computed from the total number of grains counted in each of these groups, rather than a

[25] A small sample splitter designed by G. H. Otto, and described in *Comparative tests of several methods of sampling heavy mineral concentrates*, Jour. Sed. Petrol., vol. 3 (1933) p. 30-39.

[26] A colorless artificial resin with an index of refraction of 1.5354.

[27] R. Dana Russell: *Frequency percentage determinations of detrital quartz and feldspar*, Jour. Sed. Petrol., vol. 5 (1935) p. 109-114.

[28] An organic compound whose amorphous form has an index of refraction of approximately 1.68.

[29] A. L. Dryden: *Accuracy in percentage representation of heavy mineral frequencies*, Nat. Acad. Sci. Pr., vol. 17 (1931) p. 233-238.

TABLE 1.—*Mineral composition of Mississippi River sands*

	Mile No. of Sample Localities															
	7	25	55½	78	100½	128	144	146	176	200	225	250½	272½	293¾	300¾	324½
LIGHT SEPARATES (Frequency per cent of minerals in 100-mesh grade)																
1. Chert and fine-grained quartzite	8	3	4	5	7	6	7	13	4	6	4	4	5	7	9	5
2. Other rock grains	3	9	5	9	6	9	9	6	11	8	11	9	11	7	8	11
3. Quarts	62	60	62	58	59	60	60	58	58	61	59	63	59	59	63	60
Feldspars																
4. Oligoclase and andesine	9	14	15	13	16	14	9	10	16	12	16	14	17	15	4	10
5. Albite	P	P	R	P	P	P	P	1	P	P	P	R	P	P	P	P
6. Calcic plagioclase	R	P	P	P	P	P	P	P	P	P	P	P	P	P	R	R
7. Microcline	5	6	5	5	5	5	8	5	6	5	4	5	4	6	6	6
8. Orthoclase and sanidine	3	P	1	1	1	1	3	3	P	1	1	2	1	2	1	1
9. Weathered feldspar	8	5	5	6	4	4	4	4	4	4	4	2	3	3	6	6
10. Clay grains	....	1	P	P	....	P	R	R	....	R	R	....	R	R	R	....
11. Muscovite	R	....	R	....	R	....	R	R	....	....	....	R	....	R	R	....
12. Serpentine and/or chlorite	P	R	....	....	R	....	P	P	....	P	....	....	....	P	R	R
13. Calcite	R	P	P	P	....	P	R	R	R	....	P	P	R	P	P	....
14. Glauconite	....	....	R	....	....	....	....	R	....	R	....	....	....	R	R	....
15. Volcanic glass	P	....	....	R	R	....	R	P	....	R	R	....	....	....	R	....
16. Carbonaceous matter	....	R	....	P	....	....	R	R	....	1	....	....	....	P	P	R
HEAVY SEPARATES																
Grades averaged (mesh)	150 200	150 200	150 200	150 200	150 200	150 200	65 200	150 200	150 200	150 200	150 200	150 200	150 200	150 200	150 200	150 200
Weight per cent of magnetic separate	41	12.5	26.2	25.0	43.5	23.4	11.7	12.0	31.7	21.5	12.4	28.1	26.7	23.0	9.6	8.2
Weight per cent of magnetite	41	9.1	9.9	8.7	31.4	18.0	10.5	9.5	21.1	9.7	10.5	23.9	13.6	11.8	1.2	5.1
Frequency per cent of other minerals on basis of 100 per cent																
1. Ilmenite (incl. some chromite)	27	13	22	9	36	24	24	13	37	17	12	39	24	24	6	17
2. Leucoxene	P	2	3	2	1	2	2	3	2	1	3	2	3	1	P	4
3. Limonite and hematite	12	4	4	4	2	2	3	4	3	7	3	3	4	17	7	4
4. Pyrite	7	8	6	45	1	8	1	4	4	4	4	4	11	4	6	R
5. Rock grains	2	2	2	2	7	3	18	2	2	6	4	2	2	5	6	14
6. Epidote	3	8	8	7	5	5	7	4	6	6	9	3	6	4	6	4
7. Zoisite	R	R	R	....	P	R	R	R	R	P	R	X	P	R	P	R
8. Allanite	....	P	P	....	R	P	R	R	P	P	P	1	P	R	R	....
9. Biotite	R	R	X	R	R	X	R	R	X	R	P	....	X	R	1	....
10. Olivine	R	....	R	....	P	R	R	R	R	R	R	X	X	P	R	....

Pyroxenes																
11. Augite and diopside	7	12	12	4	4	10	5	8	7	8	13	6	7	3	5	15
12. Diallage	P	2	2	P	P	1	1	1	1	P	2	2	1	P	P	R
13. Brown pyroxene	P	1	P	P	R	P	2	P	P	R	P	P	P	P	P	R
14. Hypersthene	P	2	1	1	1	P	1	1	1	1	P	P	1	P	P	P
Amphiboles																
15. Common hornblende	5	8	4	3	3	5	4	5	3	3	10	4	5	2	2	7
16. Blue-green hornblende	1	3	1	1	1	2	1	1	2	3	2	P	2	P	3	6
17. Basaltic hornblende	P	P	P	R	R	P	P	P	P	R	P	R	P	....	R	R
18. Actinolite and tremolite	1	3	4	3	2	5	2	1	2	3	5	2	4	2	3	P
Accessories																
19. Apatite	P	P	P	R	P	P	P	1	P	1	1	P	P	P	P	P
20. Zircon	3	3	4	1	3	4	4	2	6	3	2	4	2	2	1	P
21. Titanite	P	1	2	P	P	P	P	P	1	1	2	P	1	P	P	3
22. Rutile	P	P	R	X	....	R	....	R	R	....	R	P	R	R	X	R
23. Monazite	R	P	P	P	P	P	....	P	P	P	P	P	P	R	R	R
24. Staurolite	....	R	P	R	R	R	R	R	R	R	R	R	P	R	....	....
25. Andalusite	X	....	X	X	....	R	....	....	....	....	....	X	....	....	....	....
26. Sillimanite	P	R	R	X	....	R	P	R	X	R	X	....	R	....	X	R
27. Kyanite	....	P	1	X	....	R	R	R	X	R	R	R	R	R	....	R
28. Chloritoid	....	....	....	....	....	....	....	....	....	....	R	....	X	....	....	....
29. Tourmaline (a)	P	P	R	....	R	R	R	R	R	R	R	R	X	R	X	P
30. Tourmaline (b)	P	R	R	X	R	R	R	R	R	R	P	R	R	....	R	R
31. Tourmaline (c)	X	X	X	R	R	R	....	....	P	R	R	R	R	R	R	P
32. Garnet (a)	5	10	9	3	9	12	7	5	9	7	8	11	9	5	2	6
33. Garnet (b)	R	R	R	R	R	P	P	R	R	R	R	R	R	R	....	R
34. Garnet (c)	P	2	P	P	P	1	P	P	1	P	P	R	1	P	R	2
35. Dolomite and siderite	27	12	9	8	17	11	14	39	8	21	14	8	11	24	47	11
36. Collophane	R	P	P	R	R	R	R	P	R	R	P	P	R	R	P	1
Ratios: Quartz to quartz plus total feldspar	71	70	70	70	69	70	72	73	69	74	70	72	70	69	79	72
Fresh feldspar to total feldspar	69	80	81	77	85	83	83	83	86	81	85	90	89	87	65	75
Total pyroxenes	8.5	16.2	15.6	6.4	6.5	12.3	9.6	10.8	10.7	10.4	17.1	9.7	9.9	4.7	6.7	16.0
Total amphiboles	8.5	13.8	10.3	7.9	6.8	12.3	7.6	7.7	6.9	9.6	18.1	6.6	11.6	4.3	7.8	14.3
Total zircon, titanite, rutile, and monazite	5.1	5.6	6.3	2.6	4.3	5.0	4.1	3.1	8.0	4.1	4.1	6.3	4.4	3.1	1.6	4.2
Total garnets	5.9	11.8	10.0	3.1	9.8	13.6	8.2	5.8	10.9	7.9	9.0	11.9	10.6	5.3	2.0	7.9

P = Present in amounts less than one per cent but fairly common.
R = Rare.
X = Rare in one of the two grades analyzed and absent in the other.

TABLE 1.—*Mineral composition of Mississippi River sands (continued)*

	Mile No. of Sample Localities															
	349	378½	398½	404½	423	452½	475	498¾	526	549½	578	600	604¾	635	650	671
LIGHT SEPARATES (Frequency per cent of minerals in 100-mesh grade)																
1. Chert and fine-grained quartzite	4	6	6	4	3	3	3	6	5	4	3	4	2	3	6	4
2. Other rock grains	9	12	10	5	7	16	10	7	9	8	6	4	8	9	12	7
3. Quartz	62	57	62	68	65	61	60	64	63	64	64	67	65	62	64	68
Feldspars																
4. Oligoclase and andesine	12	12	9	13	12	9	16	12	12	14	14	10	11	15	7	9
5. Albite	R	R	1	P	P	R	R	P	P	P	1	P	P	P	P	1
6. Calcic plagioclase	P	R	P	P	P	R	P	P	P	P	P	P	R	P	R	P
7. Microcline	4	7	6	5	5	3	4	4	7	4	5	6	8	5	5	6
8. Orthoclase and sanidine	3	2	2	1	2	2	1	1	P	1	1	3	1	1	1	1
9. Weathered feldspar	5	3	2	2	4	4	4	4	3	5	3	5	3	3	3	3
10. Clay grains	R	R	R	....	P	....	R	R	....	....	....	R	....	P	R	....
11. Muscovite	....	R	R	R	....	P	R	R	....	....	....	....	....	P	....	....
12. Serpentine and/or chlorite	....	....	R	....	....	P	R	P	....	R	R	R	....	R	R	....
13. Calcite	1	P	P	R	P	P	P	P	P	P	1	R	2	P	P	P
14. Glauconite	....	....	R	R	....	....	....	....	....	....	....	....	....	P	....	....
15. Volcanic glass	....	R	R	R	....	....	R	R	R	....	....	R	....	....	R	....
16. Carbonaceous matter	R	....	R	....	....	R	....	R	....	R	....	R	....	R	R	....
HEAVY SEPARATES																
Grades averaged (mesh)	150 200	150 200	150 200	150 200	150 200	150 200	150 200	200	150 200	150 200	150 200	150 200	150 200	150 200	150 200	150 200
Weight per cent of magnetic separate	27.1	8.6	29.0	24.5	15.6	34.6	40.5	8.8	13.3	26.1	15.8	18.0	22.7	20.8	13.0	16.8
Weight per cent of magnetite	17.6	7.7	15.6	19.9	13.0	0.9	5.9	8.6	13.2	14.7	12.8	8.5	17.7	18.1	10.7	9.0
Frequency per cent of other minerals on basis of 100 per cent																
1. Ilmenite (incl. some chromite)	27	22	28	24	29	14	41	16	22	44	38	15	38	37	22	26
2. Leucoxene	2	4	2	1	4	5	1	2	2	1	1	P	1	1	2	1
3. Limonite and hematite	5	3	5	1	3	6	15	1	3	10	11	8	4	2	4	7
4. Pyrite	6	R	6	4	2	7	12	P	2	13	9	5	5	11	R	25
5. Rock grains	1	2	3	4	3	5	2	4	4	2	3	4	3	2	5	2
6. Epidote	5	10	5	4	9	13	3	7	12	3	5	3	8	6	12	4
7. Zoisite	R	R	R	X	X	P	R	P	R	X	X	R	R	R	R	X
8. Allanite	....	R	R	R	1	P	P	P	P	R	P	P	P	P	P	R
9. Biotite	R	P	R	R	X	1	R	R	X	X	X	....	R	R	X	X
10. Olivine	R	....	R	P	R	....	....	R	X	....	X	R	....	....	....	....

Pyroxenes																
11. Augite and diopside	6	12	4	4	6	8	2	9	9	2	4	2	5	6	7	6
12. Diallage	P	R	P	P	P	P	R	1	1	P	P	R	P	P	1	R
13. Brown pyroxene	R	R	P	P	P	P	P	P	P	R	R	P	P	P	1	R
14. Hypersthene	2	P	P	P	1	P	P	P	1	P	1	R	P	P	1	P
Amphiboles																
15. Common hornblende	7	7	3	2	7	8	4	3	10	2	3	1	4	5	8	3
16. Blue-green hornblende	2	6	2	1	2	3	1	3	2	1	1	1	3	3	7	3
17. Basaltic hornblende	P	R	X	P	P	P	R	2	1	R	R	X	R	P	P	X
18. Actinolite and tremolite	1	2	2	2	2	2	1	5	3	P	1	1	2	1	3	P
Accessories																
19. Apatite	P	2	P	P	1	P	R	1	1	P	P	R	P	P	1	R
20. Zircon	4	R	2	1	4	2	1	2	3	3	3	1	4	3	1	2
21. Titanite	1	2	R	1	1	2	1	P	3	P	P	R	2	2	1	R
22. Rutile	P	R	R	R	P	R	R	R	R	P	R	R	P	R	R	R
23. Monazite	R	R	R	R	P	R	P	P	P	R	P	X	R	P	P	R
24. Staurolite	R	....	R	....	R	X	X	P	R	R	R	....	R	R	R	R
25. Andalusite	R	R	....	X	....	X	....	....	X	....	R	....	....	....	X	....
26. Sillimanite	....	R	X	R	X	X	....	....	P	X	X	X	R	R	R	....
27. Kyanite	R	R	P	X	R	R	X	P	X	....	R	....	X	X	P	P
28. Chloritoid	R	....	X	....	R	P	....	....	X	....	....	....	....	....	R	....
29. Tourmaline (a)	P	R	X	P	P	R	X	P	R	X	R	....	R	R	R	....
30. Tourmaline (b)	R	P	X	X	P	R	R	P	R	....	X	X	R	X	P	....
31. Tourmaline (c)	P	P	X	X	R	R	X	P	R	....	X	....	R	R	R	....
32. Garnet (a)	11	7	6	4	13	3	5	4	9	7	7	3	7	10	10	12
33. Garnet (b)	R	R	R	R	1	R	R	R	P	P	R	R	R	R	R	....
34. Garnet (c)	P	1	1	R	P	R	P	P	1	1	1	R	1	2	1	1
35. Dolomite and siderite	14	14	24	40	5	14	5	35	6	5	7	50	6	3	6	3
36. Collophane	R	2	R	P	P	P	R	P	P	R	P	R	R	....	R	....
Ratios: Quartz to quartz plus total feldspar	73	70	76	76	73	77	70	74	73	73	72	74	73	71	79	77
Fresh feldspar to total feldspar	79	88	89	90	82	76	86	81	89	81	88	80	88	88	82	85
Total pyroxenes	8.5	13.2	6.5	5.9	8.8	10.4	3.3	10.7	12.4	3.3	5.7	4.0	6.1	7.5	10.4	7.1
Total amphiboles	11.1	16.0	7.9	5.8	11.2	14.1	6.1	11.9	15.5	4.1	5.8	3.9	9.6	9.8	17.8	6.7
Total zircon, titanite, rutile, and monazite	6.2	3.0	2.3	2.3	6.0	3.7	3.5	2.7	5.7	4.0	3.7	2.0	6.5	5.3	3.8	2.9
Total garnets	11.9	8.4	7.7	4.7	14.4	4.3	5.3	4.4	11.6	8.3	8.3	4.3	8.7	12.4	11.8	13.9

P = Present in amounts less than one per cent but fairly common.
R = Rare.
X = Rare in one of the two grades analyzed and absent in the other.

TABLE 1.—*Mineral composition of Mississippi River sands (continued)*

	Mile No. of Sample Localities															
	708½	725½	760¼	760½	773½	800	826½	835½	847½	860	867½	882½	896	911	924	937
LIGHT SEPARATES (Frequency per cent of minerals in 100-mesh grade)																
1. Chert and fine-grained quartzite	4	4	6	6	6	4	4	3	3	3	6	5	3	6	5	4
2. Other rock grains	5	9	10	10	8	7	5	8	8	6	9	7	7	7	6	6
3. Quartz	63	66	61	65	67	66	67	69	74	74	66	68	71	63	69	69
Feldspars																
4. Oligoclase and andesine	15	8	7	7	9	12	12	9	8	6	7	10	7	13	5	10
5. Albite	P	P	P	P	P	P	R	P	P	R	R	R	R	P	1	P
6. Calcic plagioclase	P	R	P	P	P	P	P	R	R	R	P	R	R	P	R	P
7. Microcline	6	5	5	4	4	6	7	7	4	6	6	4	5	6	7	7
8. Orthoclase and sanidine	1	1	2	2	P	2	1	1	1	1	1	P	1	P	2	1
9. Weathered feldspar	4	4	7	6	4	2	2	2	2	3	4	3	4	3	3	2
10. Clay grains	....	R	P	P	P	R	R	R	R	P	R	....	R	R	R	....
11. Muscovite	....	....	P	R	....	R	....	R	....	....	....	....	....	....	....	....
12. Serpentine and/or chlorite	R	R	P	R	R	R	R	R	....	....	R	R	....	....	....	....
13. Calcite	P	P	P	R	P	....	P	R	R	R	P	P	P	....	2	R
14. Glauconite	R	P	R	R	R	....	....	....	....	....	....	R	....	....	R	....
15. Volcanic glass	....	....	R	....	....	....	....	R	....	R	....	....	....	....	R	....
16. Carbonaceous matter	R	P	P	....	....	....	....	....	....	....	....	....	....	R	R	....
HEAVY SEPARATES																
Grades averaged (mesh)	150–200	150–200	200–....	150–200	200–....	200–....	200–....	150–200	150–200	200–....	200–....	150–200	150–200	200–....	200–....	200–....
Weight per cent of magnetic separate	16.0	20.1	30.3	30.7	3.7	33.5	11.0	22.0	21.0	11.0	13.7	22.0	24.1	15.5	14.4	7.9
Weight per cent of magnetite	1.9	3.7	29.7	9.4	3.7	31.8	10.2	21.5	13.0	2.2	13.7	13.2	16.1	10.9	14.4	7.1
Frequency per cent of other minerals on basis of 100 per cent																
1. Ilmenite (incl. some chromite)	10	20	36	22	8	50	16	32	34	18	24	27	27	23	29	15
2. Leucoxene	1	2	4	7	1	1	2	2	1	2	2	2	R	2	2	1
3. Limonite and hematite	5	8	4	14	P	2	2	2	2	3	P	2	4	2	P	2
4. Pyrite	4	5	1	4	....	P	P	1	R	4	R	P	R	R	R	R
5. Rock grains	8	5	1	3	6	1	3	5	3	3	4	3	3	5	4	3
6. Epidote	3	8	5	4	7	5	8	6	3	4	7	6	5	5	6	7
7. Zoisite	R	X	R	R	R	R	R	X	R	R	P	R	R	R	R	....
8. Allanite	R	R	....	....	R	P	P	P	....	P	P	P	R	P	P	P
9. Biotite	R	R	P	P	R	....	R	R	X	....	P	R	1	3	R	R
10. Olivine	R	X	....	R	R	R	R	R	R	R	P	R	R	R	P	P

Pyroxenes																
11. Augite and diopside	4	9	5	4	8	3	6	5	4	4	5	6	7	4	7	5
12. Diallage	P	P	1	P	P	R	P	P	P	P	P	R	1	P	P	1
13. Brown pyroxene	P	P	P	2	P	R	2	P	P	1	P	R	P	P	P	1
14. Hypersthene	P	P	P	P	2	1	1	R	1	1	2	1	1	1	3	3
Amphiboles																
15. Common hornblende	4	6	5	4	6	1	5	4	4	2	5	8	4	2	8	12
16. Blue-green hornblende	2	5	1	2	2	P	3	2	2	P	2	2	1	2	4	3
17. Basaltic hornblende	R	R	P	P	P	P	R	P	X	R	R	R	P	P	P	P
18. Actinolite and tremolite	5	5	2	2	4	2	6	3	2	P	5	4	4	4	3	9
Accessories																
19. Apatite	1	P	1	P	P	1	1	R	P	P	P	P	1	P	1	1
20. Zircon	1	2	5	2	1	7	2	2	3	2	3	2	3	3	3	2
21. Titanite	P	2	2	P	P	P	1	P	P	P	1	P	1	2	1	2
22. Rutile	X	X	1	P	P	P	P	X	R	R	R	R	R	P	P	P
23. Monazite	R	R	R	R	P	P	P	1	P	R	P	R	P	P	P	2
24. Staurolite	R	R	P	R	P	R	....	R	R	....	P	P	R	P	P	P
25. Andalusite	....	X	....	X	....	R	....	X	....	....	....	....	....	....	....	R
26. Sillimanite	X	X	P	R	....	....	....	....	X	....	R	R	X	....	P	P
27. Kyanite	P	R	R	R	R	P	....	R	R	....	P	P	R	R	P	P
28. Chloritoid	....	....	....	X	R	R	....	X	....	....	....	R	R	R	R	R
29. Tourmaline (a)	R	R	P	P	P	R	R	R	X	....	P	R	R	P	P	P
30. Tourmaline (b)	P	X	P	P	R	P	R	R	P	....	R	R	X	R	R	P
31. Tourmaline (c)	R	X	P	P	P	R	....	R	X	R	P	R	P	P	R	P
32. Garnet (a)	4	6	6	3	5	7	7	8	6	5	8	12	9	7	16	17
33. Garnet (b)	R	R	P	P	R	P	P	R	R	P	P	R	R	P	P	R
34. Garnet (c)	P	R	1	P	R	1	1	P	P	P	1	1	1	1	1	1
35. Dolomite and siderite	42	11	17	23	44	13	29	22	26	45	25	17	24	30	6	8
36. Collophane	P	P	P	R	R	R	P	R	R	R	P	R	X	P	....	P
Ratios: Quartz to quartz plus total feldspar	71	78	74	77	79	74	75	78	83	82	78	79	80	73	79	77
Fresh feldspar to total feldspar	83	79	67	68	79	90	90	91	89	82	77	85	74	88	84	88
Total pyroxenes	5.8	11.4	6.9	6.4	10.7	4.0	9.6	7.0	5.9	7.0	8.4	8.5	8.6	5.8	11.2	9.7
Total amphiboles	10.2	16.3	8.1	8.0	12.2	4.0	13.7	8.7	8.4	3.5	12.0	13.7	9.7	8.1	15.4	24.3
Total zircon, titanite, rutile, and monazite	1.8	3.5	7.8	2.3	3.2	8.5	4.6	4.6	4.4	3.2	4.4	2.9	4.3	5.2	4.9	6.6
Total garnets	4.8	6.8	6.9	3.9	5.5	8.2	8.4	8.2	6.2	5.9	10.0	13.3	10.2	8.9	17.0	18.6

P = Present in amounts less than one per cent but fairly common.
R = Rare.
X = Rare in one of the two grades analyzed and absent in the other.

TABLE 1.—*Mineral composition of Mississippi River sands (continued)*

	Mile No. of Sample Localities													
	968½	972¼	983	994½	1004¼	1014¼	1023½	1033	1040¾	1050	1062¼	1069½	1079	1083¾
LIGHT SEPARATES (Frequency per cent of minerals in 100-mesh grade)														
1. Chert and fine-grained quartzite	6	4	2	5	4	4	2	4	3	4	8	5	4	8
2. Other rock grains	8	6	6	6	5	6	7	11	9	12	7	11	13	11
3. Quartz	67	67	68	68	69	62	70	62	66	62	68	63	56	64
Feldspars														
4. Oligoclase and andesine	5	11	12	11	8	13	11	9	11	6	4	9	14	4
5. Albite	1	1	P	P	P	P	P	P	P	P	P	P	P	P
6. Calcic plagioclase	P	P	R	R	P	P	P	P	P	R	P	R	P	P
7. Microcline	6	6	7	5	6	7	5	8	6	7	7	5	5	6
8. Orthoclase and sanidine	2	2	1	2	2	P	P	1	2	1	1	1	2	1
9. Weathered feldspar	4	2	4	3	4	5	4	4	2	5	3	5	4	4
10. Clay grains	R	R	....	R	....	P	R	R	R	P	R	P	R	R
11. Muscovite	P	....	....	....	....	....	....	....	R	....	....	R	R	....
12. Serpentine and/or chlorite	R	P	....	R	R	R	....	R	R	R	R	R	R	R
13. Calcite	R	P	R	P	P	P	P	P	P	P	R	P	P	P
14. Glauconite	R	R	R	R	R	R	R	....	R	P	R	R	P	P
15. Volcanic glass	R	....	R	....	....	....	....	R	....	R	....	R	....	R
16. Carbonaceous matter	....	R	....	....	....	R	R	....	R	....	....	R	....	....
HEAVY SEPARATES														
Grades averaged (mesh)	200	150 200	200	200	200	200	200	200	200	200	200	200	200	200 ....
Weight per cent of magnetic separate	25.9	20.3	21.1	32.2	31.5	23.7	39.1	17.5	20.4	2.8	11.0	14.4	5.0	3.6
Weight per cent of magnetite	25.9	16.7	19.0	31.2	30.9	23.2	39.1	14.9	19.0	2.5	11.0	14.4	4.8	3.6
Frequency per cent of other minerals on basis of 100 per cent														
1. Ilmenite (incl. some chromite)	41	33	36	50	60	42	35	40	34	9	21	29	11	10
2. Leucoxene	2	1	2	1	2	3	1	1	1	2	2	3	3	3
3. Limonite and hematite	P	1	2	2	2	1	1	3	1	P	2	2	P	1
4. Pyrite	R	1	P	P	P	....	R	R	P	....	....	....	....	....
5. Rock grains	2	6	3	2	1	2	2	2	2	4	2	4	4	4
6. Epidote	6	6	7	5	3	8	6	8	8	10	7	11	10	13
7. Zoisite	P	P	R	P	P	P	P	P	P	P	P	P	P	P
8. Allanite	P	P	P	P	P	P	P	P	1	P	P	P	P	P
9. Biotite	R	R	R	R	....	....	....	R	R	R	....	R	P	....
10. Olivine	P	R	R	P	R	R	R	R	P	R	R	P	R	R

Pyroxenes														
11. Augite and diopside	4	5	7	3	2	5	6	5	5	11	9	8	9	10
12. Diallage	P	P	P	P	R	P	P	P	P	P	P	P	2	1
13. Brown pyroxene	P	P	P	P	R	P	P	P	P	P	P	P	P	P
14. Hypersthene	P	P	1	P	P	1	1	2	2	2	1	1	2	2
Amphiboles														
15. Common hornblende	3	6	4	3	2	[illegible]	6	3	7	7	4	6	9	11
16. Blue-green hornblende	2	3	2	2	P	P	2	P	3	5	4	2	4	4
17. Basaltic hornblende	P	R	P	P	P	P	P	P	P	1	P	P	P	1
18. Actinolite and tremolite	3	3	4	2	P	3	3	4	5	9	5	4	7	8
Accessories														
19. Apatite	1	P	1	1	P	2	2	1	1	1	1	1	2	1
20. Zircon	6	4	5	8	9	7	3	7	6	P	4	5	1	2
21. Titanite	2	1	1	1	2	1	2	P	2	1	2	1	2	1
22. Rutile	P	R	P	P	P	P	P	P	P	P	P	P	P	P
23. Monazite	P	P	P	P	P	P	2	P	2	1	P	P	1	1
24. Staurolite	P	R	P	P	R	R	R	....	P	R	R	R	R	R
25. Andalusite	....	....	....	....	....	....	....	....	....	R	....	....	R	R
26. Sillimanite	R	R	....	....	....	....	R	....	R	R	R	R	....	R
27. Kyanite	R	R	P	P	R	R	P	R	R	R	R	R	R	R
28. Chloritoid	....	X	R	R	....	R	....	R	....	R	R	....	....	R
29. Tourmaline (a)	R	P	R	R	R	R	R	R	P	P	1	P	P	P
30. Tourmaline (b)	R	P	R	R	R	R	P	R	R	P	P	P	P	P
31. Tourmaline (c)	P	P	R	R	P	P	P	P	P	P	P	P	1	P
32. Garnet (a)	10	9	10	7	8	10	15	8	11	8	7	9	9	8
33. Garnet (b)	R	R	R	P	R	R	P	P	P	R	P	P	R	R
34. Garnet (c)	1	P	P	P	1	P	P	P	1	P	1	P	P	P
35. Dolomite and siderite	12	15	10	7	2	4	7	8	2	22	22	7	18	15
36. Collophane	R	X	P	....	R	P	P	R	R	R	P	P	R	R
Ratios: Quarts to quarts plus total feldspar	79	76	74	77	76	70	76	74	75	76	80	75	69	80
Fresh feldspar to total feldspar	78	91	82	87	83	81	79	84	74	74	80	75	83	74
Total pyroxenes	5.2	6.8	10.0	5.4	2.7	7.5	8.1	8.1	8.0	13.7	10.8	10.9	13.3	13.3
Total amphiboles	8.1	11.4	10.3	6.4	3.6	7.8	11.8	8.1	16.0	22.8	14.0	11.8	20.0	23.1
Total sircon, titanite, rutile, and monazite	8.5	6.0	7.1	10.1	11.9	9.3	7.2	8.6	9.4	3.4	6.5	7.4	4.9	4.7
Total garnets	11.4	10.0	10.5	8.0	9.2	10.8	16.2	9.1	12.4	8.7	8.3	10.5	10.2	8.2

P = Present in amounts less than one per cent but fairly common.
R = Rare.
X = Rare in one of the two grades analyzed and absent in the other.

summation of the percentages shown for the individual minerals. These data are given to tenths of a percent, but the decimal figure probably is not significant. The two ratios are given to the nearest whole number and were computed as follows: $\frac{\%\ \text{quartz}}{\%\ \text{quartz} + \text{total}\ \%\ \text{feldspar}} \times 100 = \text{quartz}$ to quartz plus total feldspar ratio, and $\frac{\%\ \text{fresh feldspar}}{\text{total}\ \%\ \text{feldspar}} \times 100 = \text{fresh}$ feldspar to total feldspar ratio. As in the totals already mentioned, the percentages used were computed from the total number of grains counted in each group. The total feldspar percentage includes weathered grains.

It will be noted that a great variety of minerals are present in the samples, as is to be expected in sands from a present-day stream draining large areas underlain by varied rock types. The average sample contains between 40 and 50 minerals, counting the varieties listed in the table.

DESCRIPTION OF MINERALS

In general, the minerals are sub-angular and possess shapes typical of a detrital mode of occurrence. Well-rounded grains and euhedral crystals are rare. No detailed description of the shapes of the various minerals has been attempted, for their typical detrital shapes have been frequently described by other workers. Exceptions to this generalization, however, as well as other noteworthy features, are discussed.

Chert and fine-grained quartzite grains consist of chalcedonic chert and chert that has suffered recrystallization to a microcrystalline aggregate of quartz grains. The latter type predominates. Coarser quartz aggregates (ordinary quartzite) have not been included here, but were placed with the quartz.

Other rock grains include several varieties of fine-grained to dominantly glassy volcanic rocks, fine-grained crystalline granitic types, some metamorphic rocks, particularly schists and slates, and a few grains of well-cemented sandstone. All grains composed of an aggregate of two or more minerals were included in this group, with the exception of those consisting almost entirely of one mineral, which were classed with the dominant mineral.

The *quartz* grains are dominantly sub-angular, and most of them are clear, though a few are stained with iron oxide. "Platy quartz," composed of several parallel or sub-parallel lamellae of slightly different optical orientation, and grains possessing parting or cleavage, are common. These greatly resemble grains of plagioclase feldspar lying upon the 010 cleavage or crystal face. Because of their abundance, a staining method was developed to facilitate percentage determinations of the quartz and the plagioclase.[20] The quartz contains a variety of inclusions, but no special study was made of inclusions either in the quartz or in the other minerals.

Feldspars, in order of abundance, are oligoclase and andesine (grouped together), microcline, orthoclase, sanidine, albite, and "calcic plagioclase" (i. e., more calcic than andesine). The last two rarely make up as much as one percent of a sample. Most of the "calcic plagioclase" is labradorite, but a few grains more calcic than labradorite were noted. Orthoclase and sanidine have been combined in the tables, though the latter may be distinguished by its glassy appearance and the prevalence of a sub-

[20] R. D. Russell: *Frequency percentage determinations of detrital quartz and feldspar*, Jour. Sed. Petrol., vol. 5 (1935) pp. 109-114.

spherical or oval shape, which appears to be an original feature and not due to abrasion. Orthoclase is about twice as abundant as sanidine.

A surprisingly high percentage of the feldspar is clear and fresh, but many of the grains included with individual types are partially altered. Any division between fresh and weathered feldspar is necessarily arbitrary; in this study, grains were classed as "fresh", and assigned to individual types, if they were readily determinable, even though somewhat altered. Grains so clouded with alteration products as to be nearly or quite opaque were the only classed as "weathered feldspar". Using this criterion, the division point between fresh and weathered will vary with size of grain, more "fresh" feldspar being present in the finer size grades of a particular sample or in finer samples, but since the 100-mesh grade was analyzed from each sample, the results are comparable.

The *clay grains* are micro- to cryptocrystalline aggregates, opaque by transmitted light and dull white by reflected light, except for a few grains stained yellow by iron oxide. As they rarely make up as much as one percent of the 100-mesh grade, no attempt was made to determine the identity of the constituent clay minerals.

The *micas* are notably rare, probably because their flaky habit allows them to remain in suspension, so that they are deposited chiefly with the silts rather than in the coarser bed material. Colorless mica, all classed as muscovite, occurs chiefly in the light separates, and biotite in the heavy fractions. Some chlorite and serpentine (grouped together) are present also, usually in the light separates.

Calcite occurs as cleavage pieces, limestone fragments, shell fragments and, rarely, as Foraminifera tests. Though rarely making up as much as one percent of the 100-mesh grade, a study of the size distribution of the minerals[21] showed calcite to be quite common in the finer size grades, where much of it occurs in the form of delicate arborescent crystals, apparently too fragile to have undergone any abrasive action.

Glauconite occurs as light yellow-green to dark bluish-green sub-spherical grains, probably derived from marine Tertiary formations outcropping in the drainage basin of the Mississippi. No glauconite casts of fossils were noted.

Volcanic glass particles are colorless to brown, with indices of refraction well below 1.535, except for a few of the rarer brown grains, whose indices are slightly above this value. The shapes, except for some of the brown grains, are those typical of glass shards, of pyroclastic origin, hence most of the glass probably has been derived from tuffs or tuffaceous sediments. Although usually rare in the 100-mesh grade, these glass shards are fairly common in the finer size grades.

Rare grains of *carbonaceous matter* may include a few fragments of carbonized wood, but most of them are of coal. They probably have been derived chiefly from the breaking up of larger pieces dropped from coal barges and steamers.

With the exception of two grains of *pyrrhotite* found in one separate, the material separated with the hand magnet consists of *magnetite* and flakes of *iron*. The latter, of course, is introduced, coming from industrial plants and from dumping grounds along the banks of the Mississippi and its tributaries, and perhaps in part from sunken ships and barges. The magnetite occurs as shiny black, roundish grains, with no coating of limonite or hematite. The iron, however, is flaky and invariably coated, partially to completely, with yellow to reddish iron oxides.

The relative amounts of magnetite and iron were estimated by inspection of the magnetic separates under a binocular microscope. At the same time, the percentage of impurities (other minerals trapped with the magnetic separate) was estimated and subtracted from the percentage of the magnetic separate. The figures given in Table

[21] R. D. Russell: *The size distribution of minerals in Mississippi River sands*, Jour. Sed. Petrol., vol. 6 (1936) p. 125-142.

1 thus represent the corrected weight percentages of the magnetic separates, and the estimated percentages of magnetite, with respect to the whole heavy separates. The difference between these two figures represents the estimated weight percentages of iron flakes.

The *ilmenite* occurs as roundish grains, similar in appearance to the magnetite, so that the magnetic separation is the easiest and most rapid method of distinguishing and separating them. Some of the ilmenite grains are partially coated with leucoxene, but most of them are free of alteration products. A few grains included here are translucent and brown on thin edges; properties indicative of chromite. The *leucoxene* grains are sub-spherical and usually dead white, though a few are stained yellow by iron oxide.

The yellow to red *iron oxides* were combined, and probably iron oxides other than limonite and hematite have been included. Most of the grains are reddish, apparently closer to hematite in composition. Crystalline hematite is, however, rare, almost all grains consisting of micro- to crypto-crystalline aggregates. Though many are rounded, sub-angular to angular grains are quite common.

Most of the grains classed as *pyrite* (some marcasite?) are globular or irregular in form but with rounded surfaces. Many consist of several globular units joined together. These shapes are reminiscent of those shown by concretions (calcareous and ferruginous, as well as pyritic) in sediments, and appear to be characteristic of pyrite formed authigenically in sedimentary rocks. Euhedral crystals and granular masses, more typical of this mineral in veins and crystalline rocks, are rare. The pyrite, therefore, probably has been derived chiefly from sediments in which it was an authigenic mineral.

Epidote, zoisite, and *allanite* occur as nearly equidimensional, roundish grains. Epidote is quite common, comprising more than ten percent of the heavy separates of some of the samples. It is highly variable both in form and in properties. The crystallinity varies from microcrystalline aggregates to individual, clear grains. The composition and properties also vary through a considerable range; from colorless grains, low in iron content, with a birefringence less than 0.020 (near clinozoisite), to iron-rich types, which are deep yellow-green, with marked pleochroism, and with a birefringence of about 0.050.

Allanite is commoner than zoisite, but rarely does either make up as much as one percent of a heavy separate. Both α and β zoisite are present, but no attempt was made to determine their relative proportion.

Allanite has only occasionally been reported in detrital sediments. It may be more common than is generally supposed, especially in epidote-bearing sediments, and has been overlooked. The following description of the properties of this mineral, as it occurs in the Mississippi River samples, may be of some aid in its identification. The grains are equidimensional or roundish and deeply colored, usually greenish brown, though some are reddish brown. The pleochroism is usually strong, X being greenish brown and Z nearly black in grains 0.075 millimeters or more in diameter, but both the pleochroism and color are somewhat variable, sometimes in a single grain. Cleavage is poor or absent, though simple twins are fairly common. The indices are somewhat variable, but α is usually greater than 1.75. The birefringence also varies, usually being between 0.010 and 0.020. All grains upon which a good interference figure were secured were biaxial, with a moderate 2V (60 to 70 degrees) and a negative sign. Dispersion of the optic axes, $\varrho > \nu$ may be noted in the lighter-colored grains and in small fragments produced by crushing the larger grains, but in the latter the dispersion is usually obscured by the deep color. The absence of crystal faces and of good cleavage prevented determination of the optic orientation, but the extinction is inclined to

the trace of cleavage, if present, and to the composition plane of the twinned crystals. In spite of the variation in its properties, this mineral is fairly easily recognized by its high indices of refraction, its rather low birefringence in comparison with minerals of similar indices, and its deep color and pleochroism.

The only other representative of the epidote group identified was piedmontite, represented by a single grain surrounded by a border of epidote. Clinozoisite was expected, but was not found.

Olivine is rare and is represented only by a few grains. Most of these were fresh, but some showed incipient alteration to serpentine.

A detailed study of several large samples probably would reveal the presence of nearly every member of the *pyroxene group*. The following have been identified: Augite, aegirine-augite, aegirine, diopside, diallage, pigeonite, a brown to lavender-brown pyroxene (probably ferriferous augite and, in part, titaniferous augite), enstatite, and hypersthene. The first four were combined because the normal augite, which is most common, showed all gradations into diopside, on one hand, and into aegirine-augite, on the other. Aegirine-augite is rare, and aegirine very rare, but colorless augite, close to diopside in properties and composition, is common. True diopside probably is fairly common, but no attempt was made to distinguish it from augite. Under diallage were included all grains with a well-developed parting parallel to 100. Most of these grains are probably diopside, but some are definitely augite.

The brown pyroxene was separated during the preliminary work because its color appeared distinctive. It seemed possible that at least some of these grains were schefferite or jeffersonite, but qualitative tests for manganese were negative. Probably most of the grains included in this group are a brownish variety of normal augite or ferriferous augite, with some grains of titaniferous augite. As the work progressed, it was found that gradations exist between the brownish pyroxene and the normal augite.

Only one grain of pigeonite and two of enstatite were identified, but hypersthene is fairly common. The hypersthene varies considerably in iron content, as evidenced by the depth of color and pleochroism. Some grains, 0.06 millimeter thick, are nearly colorless; others of the same thickness are deeply colored and strongly pleochroic. In most grains of this size the distinctive pleochroism is quite evident and, of course, is still more so in the larger grains.

Gradations between the minerals of the *amphibole group* are just as evident as between those of the pyroxene group. Because of the complete gradation between tremolite and actinolite, these were combined, but actinolite is by far the commoner. Intermediate types are also present between common hornblende and basaltic hornblende, common and blue-green hornblende, and between common and blue-green hornblende and actinolite. These intermediate types are not so common, however, as to make the distinction of the varieties troublesome; hence, they were separated in the counts.

The "common hornblende" includes all grains in which the pleochroism is in shades of brownish green or greenish brown. The "blue-green hornblende", on the other hand, is a soda-rich type with Z greenish blue or bluish green, Y green or bluish green, and X yellowish green. Probably several varieties of hornblende have been included here. Some may have come from igneous rocks, but most of the blue-green hornblendes seem to be related to the glaucamphiboles and, hence, more characteristic of metamorphic rocks.

The "basaltic" hornblende, or oxyhornblende, shows the typical deep pleochroism in red-brown, small extinction angle, and high birefringence. It rarely makes up as much as one percent of the heavy separate, but is present in nearly every sample.

In addition to these amphiboles, one grain each of gedrite and glaucophane were identified.

The term *accessory*, as used here, refers to only the minor, usually microscopic, accessory minerals of crystalline rocks. Apatite, zircon, titanite, rutile, and monazite are present in nearly every slide, though only in minor amounts. Zircon is the most abundant, comprising more than five percent of the heavy separates of some samples, followed, in order of abundance, by titanite, apatite, monazite, and rutile. The last two rarely make up as much as one percent of the heavy separates.

Most of the zircon is colorless, though a lavender variety is not uncommon, and some grains are brownish. There is much well-developed zoning. Most of the grains are angular fragments or euhedral crystals, but a few well-rounded grains, presumably derived from sediments, were seen. The apatite grains are sub-angular to rounded. The titanite almost never shows good crystal form, angular to sub-angular grains being most abundant, with a few rounded ones. Pale brown or yellow grains are most common, but all gradations occur from colorless to fairly deep brown. The rutile is chiefly of the brownish-red variety, but lighter, brown grains, are also present. A few euhedral crystals and rounded grains of rutile were seen, but most are sub-angular. Knee-shaped twins are rare. The monazite is pale yellow, with faint, though distinct, pleochroism, and usually shows the typical oval or egg shape. A few grains of titanite, in which the anomalous interference tints, produced by the strong dispersion, were not evident, may have been included with the monazite in determining percentages.

Staurolite, andalusite, sillimanite, and *kyanite* are rare, hardly ever composing as much as one percent of the heavy separates. Staurolite and kyanite are the most common. Two varieties of sillimanite are present; clear individual grains and "fibrolite", the latter somewhat more common. Andalusite was only found in a few slides.

Only a few grains of *chloritoid* were found. They are usually tabular on the 001 cleavage, and pale slate-blue or bluish green with distinct pleochroism (X = bluish green to olive-green, Y = greenish blue to slate-blue). The pleochroism, low birefringence ($\gamma - \alpha = 0.010 \pm 0.002$, $\beta - \alpha$ very low), and high indices, are characteristic. The indices are lower than those given by Winchell,[22] α being $1.712 \pm .005$, but agree with Boswell's data.[23]

The *tourmalines* range from euhedral crystals and angular fragments to well-rounded grains. Three varieties, based on color and pleochroism, are listed in Table 1, but four were distinguished, the fourth being very rare. They are: (a) pleochroic in shades of yellow or brown to black or dark greenish brown; (b) yellow or brown to dark olive-green; (c) colorless or pale yellow to yellow or brown (this is a low iron-content type, probably dravite, with ω usually less than 1.650); and (d) colorless or pink to deep blue. All varieties together make up less than two percent, and in most cases, less than one percent, of the heavy separates containing them.

The *garnets* occur as angular to subangular grains, usually without crystal form. Three types were distinguished: (a) colorless; (b) yellow to pale brown; (c) apricot-yellow to pink. It is recognized that the depth of the color is largely a function of the thickness of the grain, and an attempt was made to allow for this factor

[22] A. N. Winchell: *Elements of optical mineralogy*, third edition (1933) pt. 2, p. 438-439. John Wiley and Sons, New York.

[23] P. G. H. Boswell: *The petrography of the sands of the Upper Lias and Lower Inferior Oolite in the west of England*, Geol. Mag., vol. 61 (1924) p. 254-256.

in working with various size grades. The distinction was facilitated by the fact that all the grains in a particular slide were of nearly the same thickness.

Dolomite and *siderite* occur as euhedral rhombs, as subangular to rounded grains, and as microcrystalline aggregates. Dolomite is at least ten times as abundant as siderite, but, due to the difficulty in distinguishing many of the grains, they were combined. This difficulty is due to several factors: first, some of the dolomite is stained with iron oxide, resembling the weathered siderite in color; second, the deep color of most of the siderite and stained dolomite, together with the presence of inclusions, make index determinations difficult unless the grains are isolated and crushed; and third, intermediate types (ankerite and ferrodolomite) are present.

Although Martens[34] has discussed the occurrence of detrital *collophane*, it has rarely been reported in clastic sediments. Probably in many cases this is due to the fact that the samples studied have been treated with acid, which dissolves collophane. Rogers[35] has described the properties of collophane, and additional data on grains observed in the Mississippi River samples are here given to show the similarity between the detrital grains and the fossil bone studied by Rogers.

The collophane was only noted in the heavy separates, hence its specific gravity is greater than 2.85. It is most abundant in the coarser size grades, where it may comprise up to six percent of the heavy separate, but a few grains occur in the finer grades. Almost all the material is fossil bone, many grains showing the Haversian canals and lacunae, which appear as dark lines and spots. The grains are highly variable in shape, most of them being irregular and subangular to rounded, but a few teeth and long narrow bones were noted. Under the binocular microscope (reflected light), the collophane grains are brown to deep reddish brown or nearly black. They are translucent with a vitreous to resinous luster. Under a petrographic microscope (transmitted light), the color varies from pale yellow to deep reddish brown. No grains showing pleochroism were noted, but almost every grain is anisotropic. Many are fibrous, with X parallel to the fibers, and with undulatory extinction. The birefringence varies from zero to about 0.010, the average being about 0.005. A grain showing somewhat higher birefringence than most gave the following indices: $\alpha' = 1.603 \pm .003$, $\gamma' = 1.612 \pm .003$, $\gamma' - \alpha' = 0.009$. The indices are somewhat variable, but for most grains lie between 1.600 and 1.610.

In addition to the minerals listed in Table 1, others were found in a few slides, usually only one to a slide. Because of their rarity, these were left out of the table, but some of them have been already described. In the order of the number of grains of each found, these are: barite; a variety of tourmaline pleochroic in pale pink or colorless to deep blue; green and brown spinel (?); gold; anatase; the pinite variety of cordierite; and opal (the last two in the light separates). Five or more of each of these were found. Three grains of moissanite were found, two each of brookite, enstatite, and pyrrhotite, and one of each of the following: azurite, cassiterite, gedrite, glaucophane, graphite, piedmontite, pigeonite, and sphalerite.

These, together with the minerals listed in Table 1, make a rather imposing list, yet the absence of several rather common detrital minerals is noteworthy. For example, no topaz was found, even though the possibility that it might be present was kept in mind during the examination of the slides. Also, in view of the presence of many zinc deposits within the drainage basin of the Mississippi, the absence of zinc minerals (except for one grain of sphalerite) seems unusual. Probably a detailed

[34] J. H. C. Martens: *Detrital collophane*, Am. Mineral., vol. 17 (1932) p. 153-155.

[35] A. F. Rogers: *Collophane, a much neglected mineral*, Am. Jour. Sci., vol. 203 (1922) p. 269-276; *Mineralogy and petrography of fossil bone*, Geol. Soc. Am., Bull., vol. 35 (1924) p. 535-556.

study of several large samples would reveal the presence of these minerals and many others that are too rare to have been represented in the slides examined.

VARIATIONS IN MINERAL COMPOSITION

VARIATIONS INDUCED BY LOCAL DIFFERENCES IN SIZE OF GRAIN AND DEGREE OF SORTING

The effect of differences in average grain size and in degree of sorting upon the mineral composition of the samples has been mentioned previously and has been described in another paper.[36] Variations between samples, due to differences of this type, are so great as to largely obscure any progressive downstream changes in mineral composition that might be present, but the method of comparison used eliminates most of the variations of this type. Exceptions to this are the very heavy minerals, particularly ilmenite and magnetite. These minerals are particularly susceptible to the effects of sorting, with the result that they tend to be highly concentrated in the finer grades of well-sorted samples. The method of comparison failed to smooth out all these variations, as is evident from the marked fluctuations in percentages of these minerals, shown in Table 1 and Plate 1. As the magnetite was removed from the heavy separates before frequency percentages of the other minerals were determined, variations in the percentage of this mineral do not affect the percentages of the others. This is not true of the ilmenite, however, hence a marked increase in the percentage of ilmenite, from one sample to the next, is accompanied by a decrease in the percentages of most of the other minerals (Pl. 1).

The percentage of dolomite (with which some siderite is included) also fluctuates considerably. The specific gravity of this mineral is close to that of the bromoform used to separate the "heavy" minerals from the "light" portion of the sample. Hence, differences in the specific gravity of the bromoform used, or in the rapidity with which the separations were made, to some extent determine the amount of dolomite in the heavy separate. A rapid separation may be incomplete, resulting in some of the dolomite being left with the "lights", whereas the use of bromoform whose specific gravity is somewhat below normal, or a slow and careful separation, will effect a nearly complete concentration in the "heavy" portion. The fluctuations in percentage of this mineral are probably chiefly due to these factors.

PROGRESSIVE DOWNSTREAM VARIATIONS

In any study of progressive changes in the character of sediments, the effects of addition of new material must be considered. This is especially

[36] R. D. Russell: *The size distribution of minerals in Mississippi River sands*, Jour. Sed. Petrol., vol. 6 (1936) p. 125-142.

true of stream sediments, where the influx of material from tributaries results in continued dilution of the sediment in the trunk stream. In some cases this factor may so predominate that progressive changes of other types are obscured. Fortunately, this is not the case in the lower Mississippi River. From Profit Island, just above Baton Rouge, to the Gulf, no tributary enters the Mississippi. This section of the river is a natural flume, in which the effects of transportation upon the character of the transported sediments can be studied in the absence of the complicating factor of tributary dilution. This stretch was therefore studied in greater detail than the rest of the river, the samples analyzed being spaced at intervals of about 10 miles, as far as samples were available; above Profit Island the intervals are approximately 25 miles. Even the section between Cairo and Profit Island, however, appears to be more favorable for a study of progressive changes than most streams. Only four important tributaries enter the river throughout this stretch—the St. Francis, the White, the Arkansas, and the Red. Samples from each of these streams have been analyzed.[37] The mineral composition of samples from near the mouths of these streams is similar to that of the Mississippi bed material, but the proportions of the various minerals are sufficiently different to enable the bed materials of the tributaries to be distinguished from each other and from that of the Mississippi. Immediately below the mouth of each of these tributaries, the effect of the entrance of tributary bed load can be detected in bed-material samples from the Mississippi, but in 5 or 10 miles this effect becomes indistinguishable, and the Mississippi bed material appears to be essentially the same as that above the mouth of the tributary. One sample from each of these tributaries was also studied in detail from the standpoint of roundness and was compared with samples from the Mississippi above and below the mouth of the tributary. The effect of tributary dilution could not be detected.[38]

These data are not sufficiently complete to determine accurately the relative amounts of bed load contributed by each of these tributaries in comparison to the volume of Mississippi bed load and bed material, but they strongly suggest that the amount is so small that the effect of tributary dilution is lost as soon as complete mixing of the bed loads occurs. It seems safe to assume, therefore, that tributary dilution is not a major factor in the lower Mississippi River, and hence that any progressive changes in the character of the bed load and bed material must be chiefly due to the causes previously mentioned.

Progressive downstream changes in the mineral composition of the samples can be detected by studying Table 1, but are not evident on in-

[37] R. Dana Russell and L. W. Hough: *Mineral composition of sands from Mississippi River tributaries.* In preparation.

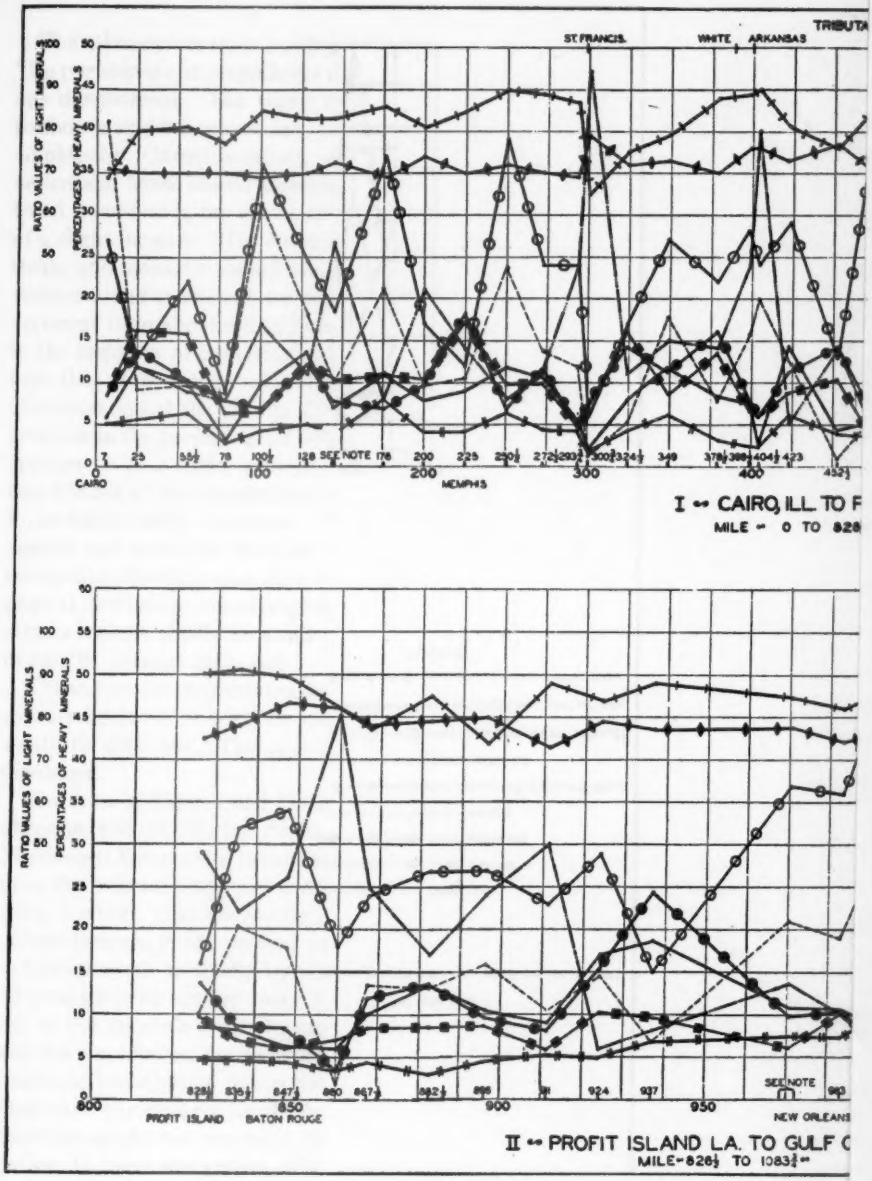
[38] R. D. Russell and R. E. Taylor: *op. cit.*

spection. A graphical presentation of the most important features is therefore given in Plate 1. As the average sample contains between 40 and 50 minerals, a grouping of related minerals is necessary to avoid confusion, and, in addition, some of the minerals have been omitted. Percentages of minerals in the heavy separates are shown for ilmenite, magnetite, dolomite and siderite, garnets, the pyroxene group, the amphibole group, and a group consisting of zircon, rutile, titanite, and monazite. Relative amounts of quartz and feldspar are shown by the quartz-to-quartz-plus-total-feldspar ratio. The relative amount of fresh feldspar, in comparison to the total feldspar content, is also shown by a ratio. The method of computing these ratios has been previously noted.

Inspection of Plate 1 shows that the various curves fluctuate, due to local variations in mineral composition not entirely eliminated by the method of comparison used, but no marked progressive changes are evident. Some slight progressive changes are shown, however, hence a consideration of the individual curves is desirable.

If the relative resistance of the various minerals to abrasion and chemical weathering is important, the quartz-to-quartz-plus-total-feldspar ratio should increase markedly downstream, due to the destruction of the feldspar and a resultant relative increase in the amount of the resistant quartz. An inspection of this curve does show a fairly uniform, though slight, increase. The average value of this ratio is about 70 for the upper part of the river, whereas it is approximately 75 near the mouth. This means a decrease of about five percent in the feldspar content. As the average total feldspar percentage in samples from the vicinity of Cairo is between 25 and 26 percent, this represents a loss of about one fifth of the feldspar in the course of 1100 miles of transportation. This is an appreciable loss, but is insignificant compared with Mackie's results (see footnote 6), which indicate that half the feldspar is destroyed in 30 or 40 miles of transportation.

Data on the resistance of the feldspars to weathering during transport is given by the curve for the ratio of fresh feldspar to the total feldspar content. Theoretically, this curve should show a decrease downstream, due to an increase in the amount of weathered feldspar. The curve fluctuates somewhat, but no pronounced decrease is evident, though there appears to be a slight decrease for the last 250 miles. This curve alone could hardly be considered to furnish conclusive evidence, for the weathered feldspars would be the first to be removed by abrasive action. In conjunction with the curve for the quartz-to-quartz-plus-total-feldspar ratio, however, it suggests that the destruction of feldspars, by abrasion, by weathering, or by a combination of these factors, is a slow process in a stream like the Mississippi.


TRIBUTA
ST. FRANCIS.
WHITE
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PERCENTAGES OF HEAVY MINERALS
SEE NOTE
CAIRO
MEMPHIS
I — CAIRO, ILL. TO F
MILE — 0 TO 828
PROFIT ISLAND
BATON ROUGE
NEW ORLEANS
SEE NOTE
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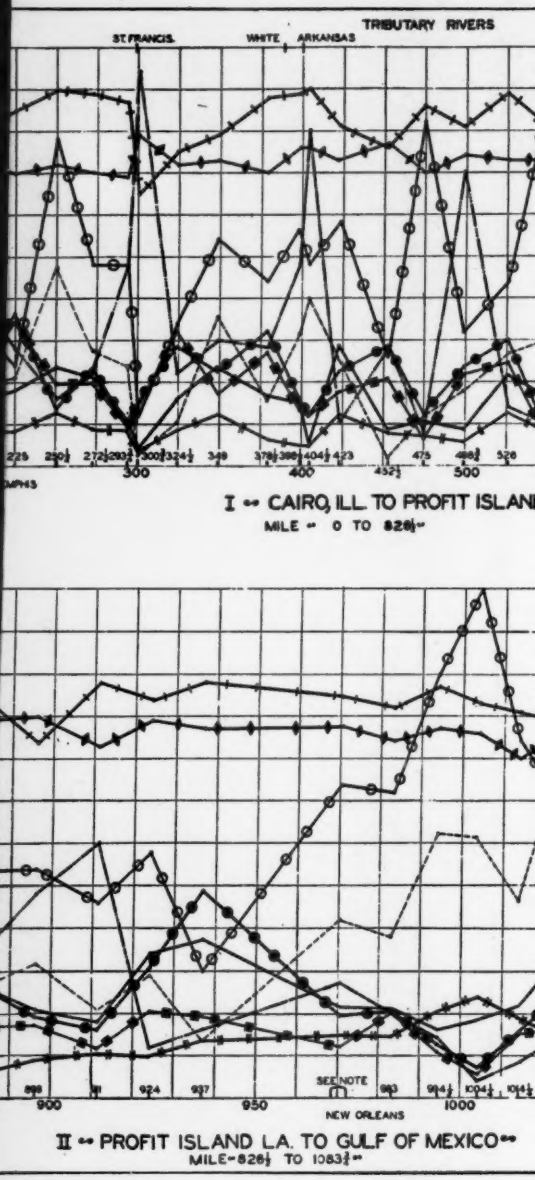
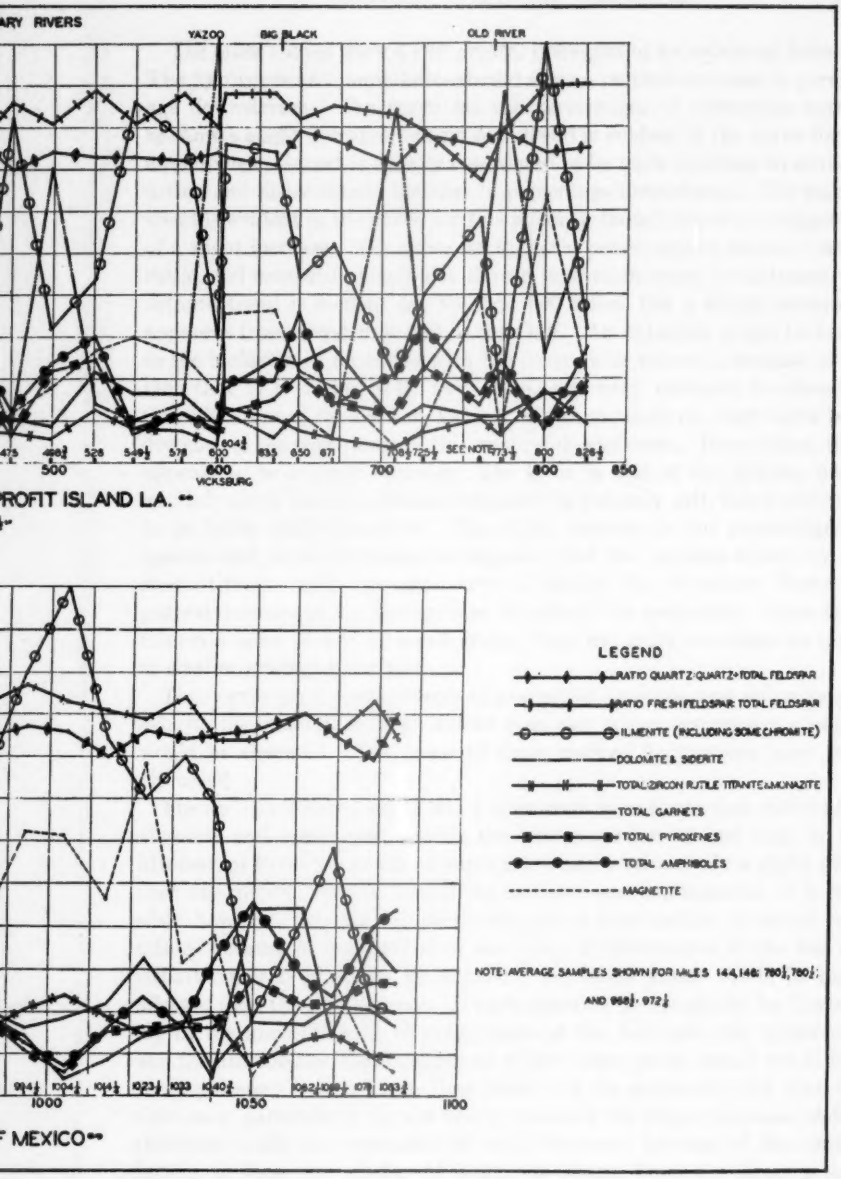
MILE-826½ TO 1083¾—



RIATIONS IN THE MINERAL COMPOSITION OF MISSISSIP



OF MISSISSIPPI RIVER SANDS

The other curves show a still greater disregard of hypothetical behavior. The pyroxenes and amphiboles should show a marked decrease in percentage downstream. The curve for the percentages of pyroxenes appears to show a slight decrease, but no such trend is evident in the curve for the amphiboles. Garnet is usually considered to be quite resistant to abrasive action and hence should increase in percentage downstream. No marked trend is evident in the curve for this mineral, though there is a suggestion of a slight increase. The curve for the total percentage of zircon, titanite, rutile, and monazite should also show a marked increase downstream. No definite trend is evident for the first 900 miles, but a slight increase is apparent from about mile 900 to the Gulf. An objection might be raised to the inclusion of monazite with the other three minerals because of the fact that it is rather soft, and, hence not very resistant to abrasion. Consideration of the data in Table 1 will show, however, that there is no decrease in the percentage of this mineral downstream. If anything, there appears to be a slight increase. The same is true of the apatite, which was left out of the calculations because it is not only soft, but is supposed to be fairly easily dissolved. The slight increase in the percentages of apatite and monazite therefore suggests that the increase shown by the zircon-titanite-rutile-monazite curve is chiefly due to another factor—a general decrease in the average size of grain of the sediments. Since these minerals occur chiefly as small grains, they are more abundant in sands of smaller average grain size.

The curves for the percentages of magnetite, ilmenite, and dolomite and siderite fluctuate to such an extent that any minor progressive changes would be obscured. The cause of these marked fluctuations have been discussed.

The data in Table 1 and Plate 1 thus seem to indicate that differential abrasion and weathering during the transportation of bed load in the Mississippi River are of minor importance, and produce only a slight effect upon the mineral composition of the bed load and bed material. It is possible, however, that the results do not give a true picture of actual conditions because of the method of analysis. If destruction of the less resistant minerals is chiefly by abrasion, the larger grains would be more affected than the smaller ones. If such abrasion occurs chiefly by fracturing of the minerals with cleavage, such as the feldspars, the pyroxenes, and the amphiboles, the breaking up of the larger grains would result in a continual contribution to the finer sizes. As the grades studied were the finer ones, particularly for the heavy minerals, the slight decreases shown therefore might not represent the total decreases because of the contribution, to these size grades, of fragments broken from the larger grains. Another study [39] has shown that fracturing takes place in sufficient amount

[39] R. Dana Russell and R. E. Taylor: *op. cit.*

to cause a slight decrease in roundness of the coarser size grades. Whether this has an appreciable effect on the mineral composition is another matter, but a study of the size distribution of the minerals [40] yields some evidence on this point. These data are summarized in Table 2, which gives the quartz-to-quartz-plus-total-feldspar ratio, the total percentage of pyroxenes, and the total percentage of amphiboles, for each size grade of three pairs of samples from the upper, lower middle, and lower part of the stretch from Cairo to the Gulf. To reduce the effect of local variations, the values have been averaged for the two samples of a pair.

TABLE 2.—*Ratios and percentages for three selected localities*

Mile numbers of sample localities	Size grades expressed in mesh numbers								
	20	28	35	48	65	100	150	200	<200
	Quartz-to-quartz-plus-total-feldspar ratio								
144 –146	84.0	77.5	80.5	77.5	77.0	72.5	60.0	66.0	72.5
760¼–760½	79.0*	85.0*	84.0*	83.0	79.0	76.5	63.5	64.0	60.5
968½–972¼	....	....	82.5	87.5	81.5	77.5	73.0	71.5	59.0

	Percentage of total pyroxenes					Percentage of total amphiboles				
	65	100	150	200	<200	65	100	150	200	<200
144 –146	15.6	18.3	13.2	5.3	4.3	9.5	15.1	8.8	7.0	5.1
760¼–760½	11.7	12.8	8.4	6.4	2.7	8.4	15.7	16.3	7.2	2.3
968½–972¼	12.6	11.4	11.1	4.8	2.0	12.9	16.2	18.7	7.4	3.1

* For 760½ only; insufficient material for analysis in these grades of 760¼.

If the fracturing process mentioned has an important effect on mineral composition, the coarser size grades should show a more rapid downstream decrease in the percentages of feldspar, pyroxenes, and amphiboles, than the finer ones, for these minerals are being broken up more rapidly in the coarser grades and are contributing fragments to the finer sizes. Table 2 suggests such a tendency, especially for the pyroxenes and amphiboles, but it appears to be very slight. Six samples could hardly be expected to furnish conclusive evidence on this point, especially in view of the com-

[40] R. Dana Russell: *The size distribution of minerals in Mississippi River sands*, Jour. Sed. Petrol., vol. 6 (1936) p. 125-142.

plicating factor of local variations in mineral percentages, but the data suggest that this factor is of minor importance.

There is also a possibility that decreases due to abrasion and weathering have been offset by progressive downstream sorting on the basis of shape. The principles involved here have been outlined previously. Predominance of the rolling type of movement results in a downcurrent increase in the percentage of the more spherical grains; predominance of the suspension type leads to a progressively higher percentage of low sphericity grains in the direction of transport. The "less resistant" minerals, in general, possess a lower degree of sphericity than the "resistant" ones. Hence, if the suspension type of movement predominates, the tendency of the feldspars, the pyroxenes, and the amphiboles to outrun the more spherical "resistant" minerals might offset the effects of selective abrasion and weathering during transport. Fortunately, direct evidence is available concerning the importance of this type of sorting in the Mississippi River. An independent study [41] of grain shapes showed little downstream change in the shapes of the grains, at least for the sand sizes. There is a slight downstream decrease in sphericity, but the evidence indicates that this decrease is chiefly the result of a decrease in roundness produced by fracturing and chipping, rather than being due to sorting on the basis of shape. The data indicate that such sorting is not an important factor in the Mississippi River, as far as the sand sizes are concerned, and hence could have little influence on progressive changes in mineral composition.

This might be expected in view of what is known of the character of the movement of sediment in streams. Though the bed load moves largely by saltation,[42] this type of movement is essentially a combination or rolling and suspension. Therefore, movement by rolling and by suspension may be considered to be the two essential methods of transportation of sediments, saltation being an intermediate type in which either of the other two may predominate. Whether movement is dominantly by rolling or by suspension depends chiefly upon the size of the grains involved and upon the velocity and turbulence of the current. Velocity and turbulence are a function of depth, slope, and the roughness of the bed. Since, in a stream, these factors not only vary greatly from time to time, but also from one place to another in the stream's bed, due to the irregular configuration of the latter, velocity and degree of turbulence also vary greatly. Thus, although the coarsest material will be moved only periodically, and then dominantly by rolling, and the finest dominantly or entirely in suspension, grains of intermediate size will at times

[41] R. Dana Russell and R. E. Taylor: *op. cit.*

[42] G. K. Gilbert: *The transportation of débris by running water*, U. S. Geol. Surv., Prof. Paper 86 (1914) p. 26.

move chiefly by rolling and at other times chiefly in suspension. Within this range of sizes transported by both types of movement there will be a group of sizes transported about equally by each type, so that little or no sorting on the basis of shape will occur. Because of the great fluctuations in the velocity and turbulence of a stream, this group will include a wider range of sizes in stream sediments than in those transported by most other agents. In the Mississippi River, most of the sand sizes appear to fall within this group, at least the grains between 0.589 and 0.074 millimeters in diameter.

Two other possible causes of progressive changes in mineral composition—sorting on the basis of specific gravity and on the basis of size—remain to be considered. Sorting on the basis of specific gravity tends toward a progressive downstream decrease in the percentages of the heavier minerals and, conversely, a relative increase in the percentages of the lighter minerals. The heaviest minerals present in any abundance in the samples studied are magnetite and ilmenite. The curves for these minerals do not show an evident decrease in their percentages downstream, but the percentages vary to such an extent that a slight progressive change might be obscured. As more information might be given by data on the percentages of the heavy-mineral group as a whole, these are presented in Table 3 and Figure 2. Table 3 gives, in successive columns from left to right: the mile number of the samples; the size grades from which the heavy minerals were separated; the percentages, by mechanical analysis, of material in these size grades; the percentages of heavy minerals in these size grades; and the percentages of heavy minerals in these grades with respect to each sample as a whole. This last column is thus the product of multiplying the two preceding columns. In Figure 2 the data in the last column of Table 3 are presented graphically. The dotted line represents the weight percentages of heavy minerals in the 200-mesh grade, the dashed line, in the 100-mesh grade, and the solid line, in the "midway grade", each with respect to the total weight of the sample. As the 200-mesh grade is also the "midway grade" in many samples, particularly in the lower part of the river's course, these two curves coincide in places. Average values have been shown for samples 144-146, 760¼-760½, and 968½-972¼. Figure 2 shows that there is a wide variation in the percentages of heavy minerals, but that there is no progressive downstream decrease. On the contrary, the curves show a slight progressive increase. This is probably due to the fact that the heavy minerals, whose average grain size is less than that of the quartz and feldspar, are more abundant in the finer samples. The increasing number of fine samples downstream therefore results in relatively higher percentages of heavy minerals, in spite of the fact that a progressive sorting on the

R. Dana Russell: *Mineral composition of Mississippi River sands*

TABLE 3.—*Percentages of heavy separates in Mississippi River sands*

Mile number of sample	Size grade	Per cent of size grade by mechanical analysis	Per cent of heavy separate in size grade specified	Per cent with respect to whole sample
7	100	1.36	10.00	.136
	150	.08	21.20	.017
	200	.08	6.10	.005
25	100	14.21	1.12	.159
	150	1.43	10.42	.149
	200	.20	10.42	.021
55½	100	.75	7.09	.053
	150	.14	6.38	.009
	200	.04	9.26	.004
78	100	.15	6.85	.010
	150	.04	6.39	.003
	200	.04	21.54	.009
100½	100	5.65	4.20	.237
	150	.57	6.50	.037
	200	.07	2.20	.002
128	100	2.15	6.37	.137
	150	.50	7.18	.036
	200	.08	7.20	.006
144	Whole sample		2.31	2.310
	65	6.39	2.50	.160
	100	4.25	2.20	.094
	200	.20	21.76	.044
146	Whole sample		2.22	2.220
	100	1.28	9.00	.115
	150	.66	6.90	.046
	200	.11	11.07	.012
176	100	6.40	2.96	.189
	150	.53	12.81	.068
	200	.08	27.82	.022
200	100	4.80	3.20	.154
	150	.60	7.40	.044
	200	.06	6.80	.004
225	100	2.87	2.68	.077
	150	.81	3.90	.032
	200	.18	7.18	.013
250½	100	5.48	9.08	.316
	150	.43	16.95	.073
	200	.04	13.18	.005
272½	100	6.50	6.33	.411
	150	1.23	7.37	.091
	200	.11	15.27	.017
293¾	100	.52	7.50	.039
	150	.06	14.70	.009
	200	.03	25.20	.008
300¾	100	.21	4.10	.009
	150	.04	4.05	.002
	200	.04	1.10	.0004
324½	100	3.29	3.47	.114
	150	.97	3.42	.033
	200	.08	4.95	.004
349	100	6.06	3.37	.204
	150	.75	6.35	.048
	200	.25	1.05	.003
378½	100	17.55	1.49	.261
	150	2.74	2.81	.077
	200	.46	11.05	.051

TABLE 3.—*Percentages of heavy separates in Mississippi River sands (continued)*

Mile number of sample	Size grade	Per cent of size grade by mechanical analysis	Per cent of heavy separate in size grade specified	Per cent with respect to whole sample
398½	100	1.00	9.56	.096
	150	.04	11.15	.004
	200	.04	8.05	.003
404½	100	2.03	15.02	.305
	150	.36	14.80	.053
	200	.15	6.90	.010
423	100	14.72	2.38	.350
	150	2.10	9.78	.205
	200	.13	15.27	.020
452½	100	.10	33.00	.033
	150	.15	2.71	.004
	200	.26	2.40	.006
473	100	.40	23.55	.094
	150	.12	24.20	.029
	200	.06	13.91	.008
498¾	100	16.58	4.20	.696
	200	3.29	9.30	.306
526	100	10.29	4.08	.420
	150	3.81	3.86	.147
	200	1.13	7.00	.079
549½	100	6.60	16.41	1.083
	150	.63	49.04	.309
	200	.09	34.26	.031
578	100	3.79	3.50	.133
	150	.11	15.60	.017
	200	.06	21.52	.013
600	100	1.07	7.30	.078
	150	.05	18.30	.009
	200	.05	15.10	.008
604¾	100	2.97	9.80	.291
	150	.41	11.91	.049
	200	.10	11.13	.011
635	100	1.71	6.74	.115
	150	.32	11.91	.039
	200	.05	9.31	.005
650	100	26.68	3.17	.846
	150	7.18	5.06	.363
	200	1.23	12.96	.159
671	100	3.94	6.80	.268
	150	.06	6.79	.004
	200	.06	1.23	.0007
708½	100	1.32	4.00	.053
	150	.17	7.20	.012
	200	.06	10.10	.006
725½	100	.69	4.05	.028
	150	.46	2.90	.013
	200	.11	.43	.0005
760¼	Whole sample		2.10	2.100
	100	57.82	1.40	.809
	200	.66	3.20	.021
760½	Whole sample		1.30	1.300
	100	1.33	10.00	.133
	150	.12	15.99	.019
	200	.06	28.67	.017

TABLE 3.—*Percentages of heavy separates in Mississippi River sands (continued)*

Mile number of sample	Size grade	Per cent of size grade by mechanical analysis	Per cent of heavy separate in size grade specified	Per cent with respect to whole sample
773½	100	29.39	1.40	.411
	200	12.43	12.40	1.581
800	100	32.66	2.00	.653
	200	.20	49.40	.099
826½	100	25.11	.75	.188
	200	.32	8.54	.027
835½	100	7.22	1.99	.144
	150	.41	18.00	.074
	200	.06	18.30	.011
847½	100	5.22	1.22	.064
	150	.93	11.75	.109
	200	.15	16.60	.025
860	100	38.80	1.55	.601
	200	.48	15.40	.074
867½	100	48.57	.57	.277
	200	.73	7.98	.057
882½	100	5.56	1.29	.072
	150	.55	17.60	.097
	200	.12	29.61	.036
896	100	4.75	1.58	.075
	150	1.29	12.30	.159
	200	.11	17.80	.020
911	100	37.17	1.90	.706
	200	1.23	14.60	.180
924	100	48.01	1.12	.538
	200	.51	23.15	.118
937	100	45.91	1.89	.868
	200	.51	20.58	.105
968½	100	73.98	1.70	1.258
	200	2.02	43.90	.887
972¼	100	5.44	3.40	.185
	150	2.16	7.80	.168
	200	.05	47.80	.024
983	100	24.69	1.70	.420
	200	.05	8.92	.004
994½	100	35.96	1.38	.496
	200	.52	35.40	.184
1004¼	100	48.07	.69	.332
	200	.28	41.50	.116
1014¼	100	65.88	.63	.415
	200	1.23	26.00	.320
1023½	100	57.46	1.33	.764
	200	1.32	23.20	.306
1033	100	20.28	2.28	.462
	200	.26	35.80	.093
1040¾	100	68.95	.48	.331
	200	.60	22.60	.135
1050	100	49.70	.62	.308
	200	4.43	11.65	.416
1062¼	100	57.08	.80	.457
	200	1.89	19.80	.374
1069½	100	20.09	1.32	.265
	200	4.40	14.40	.634
1079	100	12.79	.44	.056
	200	8.51	16.80	1.430
1083¾	100	75.48	1.18	.891
	200	16.70	12.20	2.037

basis of specific gravity would tend to reduce the percentages of "heavies". That is, the progressive decrease in the average grain size of the sediments has a greater effect upon their mineral composition than does sorting on the basis of specific gravity.

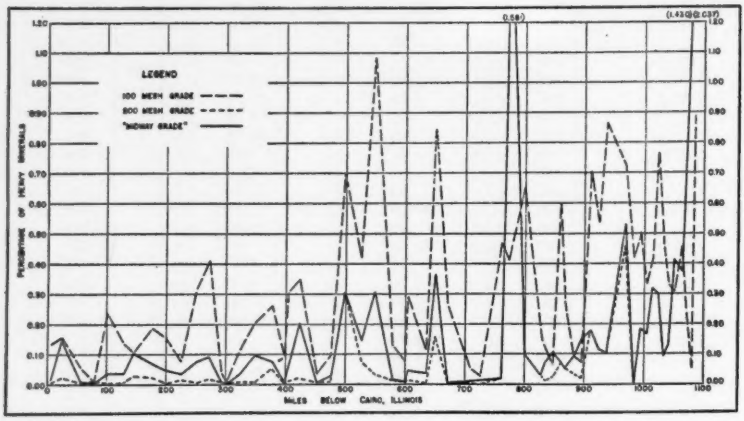


FIGURE 2.—*Variations in percentages of heavy separates in Mississippi River sands*

The effect on mineral composition of sorting on the basis of size, evidenced in the Mississippi River bed materials by a progressive downstream decrease in mean grain size, is shown by a slight increase in the percentages of apatite and monazite as well as by the increase in percentage of the heavy mineral group as a whole. These increases appear to take place chiefly in the lower part of the river's course. The decrease in average grain size of the sediments is most marked in this same stretch,[43] another indication that the decrease in grain size is responsible for the increases mentioned.

The effect of the decrease in average grain size is even more important than the data presented would indicate, due to the fact that the method of comparison used tends to reduce the effect of this factor. This is particularly true of the light minerals, which were analyzed only from the 100-mesh grade. The feldspars, especially the oligoclase and andesine, possess a smaller average grain size than the quartz, so that the percentage of feldspar is usually higher in the finer samples. This fact suggested that the downstream decrease in the mean grain size of the samples might offset the destruction of feldspar to some extent. To test this possibility,

[43] *Studies of river bed materials and their movement, with special reference to the lower Mississippi River*, U. S. Waterways Exper. Stat., Miss. River Comm., Paper 17 (1935) p. 126, pl. 59.

analyses which had been made of some of the whole samples were supplemented by additional analyses; the results are presented in Table 4. Some of the samples of Table 4 are not included in Table 1; they were studied at a later date, in connection with a study of the tributaries. Nearby samples have been averaged to reduce the effect of local variations in mineral percentages.

TABLE 4.—*Ratio of quartz to quartz plus total feldspar in whole samples*

Mile number of samples	Quartz-to-quartz-plus total-feldspar ratio
7	77
144–146	73
292–301	76
385½–396–403	76
578	78
760¼–760½	74
896	75
1079	72

Table 4 shows no evidence of a downstream decrease in feldspar content. As a matter of fact, the quartz-to-quartz-plus-total-feldspar ratio shows a suggestion of a decrease; that is, the feldspar content appears to increase slightly. Positive conclusions cannot be drawn from such a small number of analyses, but there appears to be little doubt that sorting on the basis of size offsets the effect of destruction of the feldspars during transportation to some extent. The data of Table 4 suggest that the sorting effect largely nullifies the results of destruction and perhaps is slightly predominant.

Thus it appears that selective destruction of minerals by abrasion and alteration during transport is not only a relatively unimportant process in the lower Mississippi River, but that a large part of the effect of this process is offset by other factors, with the result that sands reaching the Gulf have nearly the same mineral composition as those in the vicinity of Cairo.

PERSISTENCE OF DETRITAL MINERALS

The writer is well aware of the fact that conditions of abrasion vary greatly from one stream to another, and that data derived from a study of sediments from the Mississippi River probably are not directly applicable to streams of higher gradient and velocity. Undoubtedly a steep mountain stream has a much greater abrasive effect upon its bed load than

does the Mississippi. Yet even the maximum effects probably have been greatly overestimated, due to a failure to properly evaluate the relative effects of selective destruction during transport and of decomposition in the source rocks or in the sediment after deposition.

Probably most sedimentary petrologists will agree with Thoulet's "order of destruction" of the common rock-forming minerals contributed to sediments.[44] This is: olivine, the pyroxenes, the amphiboles, apatite, plagioclase, orthoclase, biotite, muscovite, quartz, rutile, zircon, and corundum. Now, compare this "order" with what is known of the relative resistance of these minerals to abrasion and to agents of chemical weathering.

Cozzens and Freise[45] have conducted experiments upon the relative resistance of certain minerals to abrasion by transport. Cozzens studied only a few minerals; Freise investigated a rather large number. The latter's results for some of the more common detrital minerals are reproduced in Table 5, in order of increasing resistance.

TABLE 5.—*Relative resistance of certain minerals to abrasion by transport, according to F. W. Freise*

Mineral	"Transportwiderstand" compared to crystalline hematite=100.
Monazite	105–130* av.=117
Orthoclase	150
Diopside	160
Andalusite	220
Kyanite	260
Apatite	275
Common olivine	290
Epidote	320
Ilmenite	325
Garnet	320–420* av.=378
Magnetite	380
Topaz	390
Common augite	420
Staurolite	420
Cordierite	480
Pyrite	500
Tourmaline	650–950* av.=817

All values represent averages of three determinations.

* In these cases, several specimens or varieties, differing in chemical composition, were analyzed. Determinations were made on two varieties of monazite, on five of garnet, and on three of tourmaline.

[44] J. Thoulet: *Notes de lithologie sous-marine*, Ann. Inst. Océanogr., t. 5, fasc. 9 (1913).

[45] Arthur B. Cozzens: *Rates of wear of common minerals*, Washington Univ. Stud., n. s., Sci. and Tech., no. 5 (1931) p. 71–80.

F. W. Freise: *Untersuchung von Mineralen auf Abnutzbarkeit bei Verfrachtung im Wasser*, Min. und Pet. Mitt., vol. 41 (1931) p. 1–7.

Some marked differences are evident between this list and Thoulet's "order of destruction". Most striking is the rather high resistance of augite, greater than that of topaz, garnet, and ilmenite; also the resistance of olivine, which is greater than that of kyanite and andalusite. Certainly there is no good correlation evident between this list and Thoulet's "order".

Turning to the relative resistance of minerals to solution and alteration under conditions of ordinary weathering, one finds that considerable data have been accumulated. The effects of carbonic acid and of organic acids have been especially studied. Much work remains to be done before details will be available, but the relative resistance of the common minerals under ordinary conditions of weathering has been fairly well determined.[46] The general consensus of opinion, based largely upon experimental research, indicates that this "order of resistance", for the following minerals, is: olivine, the pyroxenes, the amphiboles, the plagioclase feldspars, the orthoclase feldspars, biotite, muscovite, quartz, zircon, corundum, and ilmenite. Apatite is not readily altered, but is easily dissolved, and hence probably should be placed near the beginning of the list. Magnetite is rather insoluble in carbonic acid and organic acids, but is subject to oxidation; its position is questionable. Epidote appears to be rather easily affected by decaying organic matter. Little data are available concerning such common detrital minerals as garnet, titanite, the titanium oxides, the aluminum silicates, and tourmaline, but their common presence in ancient sediments has led to the belief that they are not easily altered nor readily soluble.

It will be seen that this list is essentially identical with Thoulet's "order of destruction", from which one may conclude that the absence of the "less resistant" minerals in sediments should be attributed largely to solution and alteration, either in the source rocks or after deposition, rather than to destruction during transport. Decomposition of minerals after deposition has been recognized by many sedimentary petrologists and, with respect to the pyroxenes and amphiboles, has been emphasized by Edelman, and by Edelman and Doeglas,[47] who have interpreted the frayed and "cockscomb" appearance of these minerals as evidence of their gradual elimination after deposition. Yet the "destruction during transport" hypothesis continues to enjoy an undeserved popularity. One of the most questionable applications of this hypothesis is in connection

[46] For discussions and lists of references on this question *see* F. W. Clarke: *The data of geochemistry*, U. S. Geol. Surv., Bull. 770 (1924) p. 481 et seq., and P. G. H. Boswell: *On the mineralogy of sedimentary rocks*, Murby and Co., London (1933) p. 37 et seq.

[47] C. H. Edelman: *Diagenetische Umwandlungserscheinungen an detritischen Pyroxenen und Amphibolen*, Fortschr. Min. Kryst. Pet., vol. 16 (1931) p. 323-324.

C. H. Edelman and D. J. Doeglas: *Reliktstrukturen detritischer Pyroxene und Amphibole*, Min. und Pet. Mitt., vol. 42 (1932) p. 482-490.

with the local presence of ferromagnesian minerals in a sedimentary horizon in which they are usually absent. Such occurrences have been interpreted, time and again, as indicating local sources for the ferromagnesians, such as erosion remnants or nearby highland areas, without considering the alternative theory that their local presence may be due to their preservation in a sealed, anhydrous environment, while they have been removed elsewhere in the horizon by alteration and solution.

The absence of the "less resistant" minerals in sediments derived from older sedimentary formations therefore should not be interpreted as chiefly due to the sediment having passed through more than one cycle of transportation, with consequent destruction of the less resistant minerals during the two or more periods of transport. Decomposition following deposition of the original sediment, accelerated when the latter is uplifted into the zone of erosion, followed by another period of decomposition after re-working and re-deposition, will, in most cases, suffice to explain the absence or the relative scarcity of pyroxenes, amphiboles, and feldspars. The fact that these minerals are present in Tertiary and Recent sediments, although not found in many Mesozoic and older formations, apparently directly derived from the same types of source rocks, is further evidence that decomposition after deposition, rather than destruction during transport, is the dominant cause of the disappearance of the ferromagnesians and feldspars. The "persistent" detrital minerals appear to be those that are most resistant to the common agents of decomposition, rather than those most resistant to abrasion.

The relative abundance of feldspars and ferromagnesians in some ancient sediments does not invalidate this thesis, nor is it evidence of closely adjacent source rocks. Such occurrences may be explained more logically as resulting from the erosion of relatively unaltered source rocks and the subsequent protection of the feldspars and ferromagnesians by cementation, or removal from the zone of alteration. The distance which the sediment has been transported does not seem to be a major factor.

SUMMARY AND CONCLUSIONS

Mississippi River bed material sands are characterized by a considerable variety of minerals, the average sample containing between forty and fifty, and by the abundance of minerals which have been considered to be rather easily destroyed during erosion and transportation.

Due to local differences in average grain size and degree of sorting, the percentages of the minerals vary considerably, but the use of a method that eliminates most of these variations permitted the comparison of samples for the determination of progressive changes in mineral composition. Changes of this kind are present, but slight. The feldspars show

the most evident progressive change, decreasing from an average of about 25 percent of the 100-mesh grade in the vicinity of Cairo, Illinois, to about 20 percent of the same grade near the Gulf. The whole samples, however, show little evidence of a downstream change in feldspar content. The pyroxenes seem to decrease very slightly, but the amphiboles maintain a nearly constant percentage or possibly increase somewhat. A group of the non-metallic accessory minerals of crystalline rocks—zircon, titanite, rutile, and monazite—remains fairly constant in percentage from Cairo to a point 900 miles downstream, then increases slightly from that point to the Gulf, a distance of about 180 miles. The percentage of garnets appears to remain fairly uniform, but a slight increase is suggested. The metallic minerals, and dolomite and siderite, fluctuate in percentage to such an extent that any slight progressive changes that might be present are obscured. The percentage of the heavy-mineral group as a whole also fluctuates considerably, but apparently increases slightly downstream.

Consideration of the possible causes of these progressive changes in mineral composition indicates that they probably are not due to tributary dilution nor to progressive sorting on the basis of shape or of specific gravity. The slight increase in percentage of the heavy-mineral group as a whole, and of the non-metallic accessory minerals of crystalline rocks, apparently is the result of a progressive sorting on the basis of size, not completely eliminated by the method of comparison used. Selective destruction by abrasion and chemical weathering during transport appears to be the cause of the decrease in percentage of the feldspars in the 100-mesh grade of the samples, but the importance of this factor appears to have been greatly overestimated. Only about one-fifth of the feldspar in this size grade is destroyed in the course of the 1100-mile journey from Cairo to the Gulf, a very slow rate of destruction compared to Mackie's results. The pyroxenes and amphiboles, usually considered to be even more easily destroyed than the feldspars, show little or no progressive loss. Even the feldspar loss seems to be largely compensated by progressive sorting on the basis of size, so that the feldspar content of the whole samples apparently remains nearly constant. The contribution of fragments broken from larger grains to the smaller sizes studied probably is a factor in the results, but it appears to be a minor one. In any case, the interaction of all the factors involved results in the maintenance of a nearly uniform mineral composition from Cairo to the Gulf, excepting for local differences resulting from variations in grain size and degree of sorting.

Since selective destruction of the "less resistant" minerals during transport appears to be of such slight consequence in the Mississippi, the importance of this action probably has been generally overestimated. This

suggestion is supported by the fact that the "order of destruction" of minerals contributed to sediments, as postulated by Thoulet and fairly generally accepted by sedimentary petrologists, agrees with an order based upon what is known of the relative resistance of minerals to decomposition, but does not agree with an order based upon relative resistance to abrasion. The "persistent" detrital minerals appear to be those that are most resistant to chemical processes, their relative resistance to mechanical action being of minor importance.

The presence in a sediment of the "less resistant" minerals, particularly the feldspars and ferromagnesians, is often cited as evidence of a nearby source. Conversely, it is often assumed that their absence may be accounted for by a few hundred miles of transportation. This hypothesis has no factual basis. Like Werner's once widely accepted Neptunistic doctrine, it owes its popularity to plausible reasoning rather than to observational evidence.

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"SALT" DOMES RELATED TO MISSISSIPPI SUBMARINE TROUGH

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INTRODUCTION

During charting operations west of the Mississippi Delta area, the United States Coast and Geodetic Survey explored in detail the submarine valley that had been discovered previously in a locality 30 miles southwest of the Passes. The writer was fortunate in being able to accompany the survey vessel during these operations. The large domes and ridges

discovered in the vicinity of the valley were not anticipated and open up a new problem for marine investigations.

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This work was assisted by a grant from the Geological Society, which covered expenses incidental to the trip. Thanks are due also to the United States Coast and Geodetic Survey and particularly to Captain F. S. Borden, of the *Hydrographer,* the vessel on which the survey was made. The coöperation of Dr. Marcus Goldman, Dr. J. B. Reeside, Mr. L. G. Henbest of the United States Geological Survey, and Mr. J. T. Richards in examining the limestone specimens and fossils was much appreciated.

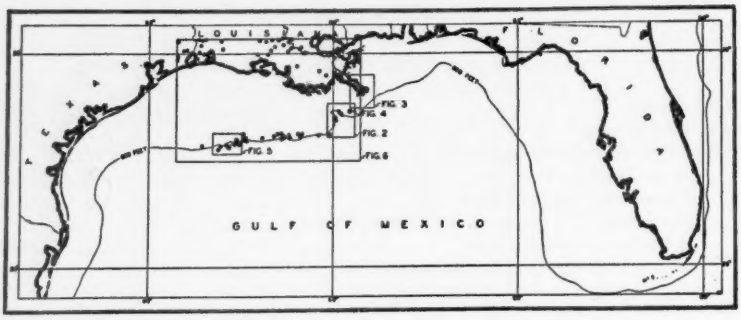

FIGURE 1.—*Key map of the area*
Dots represent location of salt domes.

MISSISSIPPI SUBMARINE TROUGH

GENERAL STATEMENT

The detailed soundings give a clear picture of the submarine valley that lies off the Mississippi Delta area. It penetrates the continental shelf about 20 miles—the maximum for the American submarine valleys. This point is of special interest because the Mississippi is the largest river in North America. The shape of the feature to be seen from an examination of Figure 2 is obviously not a typical "submarine canyon." Instead of the usual V-shaped cross-section, it has a broad, flat floor, as much as 10 miles across in the lower portions. The sides are nearly as steep as those in submarine canyons in general. On account of its shape it is appropriate to designate it a "trough." Another similar trough, although smaller and not as thoroughly sounded, is shown in Figure 5. The Mississippi submarine valley is unlike those found off glaciated regions in that the latter show large undrained depressions and other characteristics

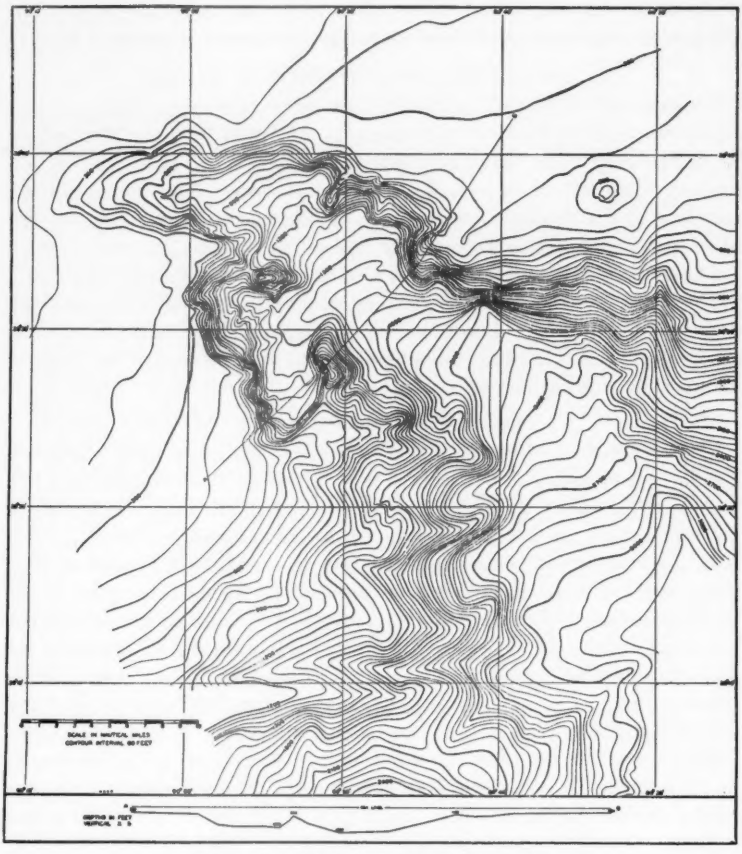

FIGURE 2.—*Mississippi submarine trough*

Showing a typical section along line A-B. Note broad flat base and steep walls. Based on detailed soundings by U. S. Coast and Geodetic Survey.

of glacial erosion,[1] whereas the Mississippi trough slopes outward continuously, and evidently at a uniform grade.

COMPARISON WITH MUD FLOWS

The only features on land with which this trough can be compared are the valleys floored with large mud flows. Slumgullion mudflow in Colorado, for example, shows the same uniform slope of its floor and has the

[1] F. P. Shepard: *Glacial troughs of the continental shelves*, Jour. Geol., vol. 39 (1931) p. 345-360.

same trough-shaped profile.[2] The only notable differences are the greater width and the gentler outward slope of the Mississippi submarine trough.

THE TROUGH FLOOR COMPARED WITH SLOPE OFF DELTA

The slope of the floor of the trough does, however, compare with another slope, the origin of which is quite certain. At South Pass the Mississippi Delta has been built completely across the continental shelf and is depositing material directly on the continental slope. The inclination of the slope of the deposit—one per cent—indicates the angle of repose for Mississippi muds. It is accordingly interesting to note that the slope of the base of the Mississippi trough is also approximately one per cent, and, furthermore, the bottom is covered by essentially the same material as that outside the delta. Additional confirmation of this inclination is the observation that the rapid advance of Southwest Pass into the Gulf is maintaining this same slope.

ORIGIN OF THE TROUGH SHAPE

The resemblance of the Mississippi trough to mud-flow valleys and the comparison of its outward slope to that off South Pass suggest that the bottom of the valley was filled with mud from the Mississippi River when the continental glaciers caused a moderate lowering of sea level.

If this feature had been a submarine valley of canyon dimensions like those found off most other coasts of the world, it would seem quite likely that the enormous outpourings of mud would have modified it, particularly when one considers the speed with which the Mississippi is extending its delta into the Gulf (more than 300 feet a year at Southwest Pass). With this in mind it might seem strange that the canyon was not entirely filled during the late Wisconsin stage of lowered sea level. Perhaps the inner portion was filled, but after the sea level rose the fill may have flowed out, re-establishing an angle of repose that might have been temporarily exceeded during the filling stage, owing to the support of the walls of the canyon.

Cores taken during the investigation showed that the floor of the trough was covered with a soft mud. On the other hand, a pipe brought up a hard, compact clay from the head of the valley; when dried, this clay developed only a few small shrinkage cracks. Analysis of the nitrogen content by R. F. Fleming showed more nitrogen in the hard clay than in the soft mud.

DALY'S MUD-CURRENT HYPOTHESIS AS RELATED TO THE TROUGH

It might be supposed that the finding of a submarine valley off the Mississippi River would favor the hypothesis offered recently by Daly[3]

[2] Ernest Howe: *Landslides in the San Juan Mountains, Colorado*, U. S. Geol. Surv., Prof. Pap. 67 (1909) pl. XX B. *See also* San Cristobal quadrangle.

[3] R. A. Daly: *Origin of submarine "canyons,"* Am. Jour. Sci., 5th ser., vol. 33 (1937) p. 369-379.

that, during low sea-level stages, currents set up by the greater weight of muddy water slide down the slope and excavate submarine canyons. An examination of the situation, however, suggests various points quite

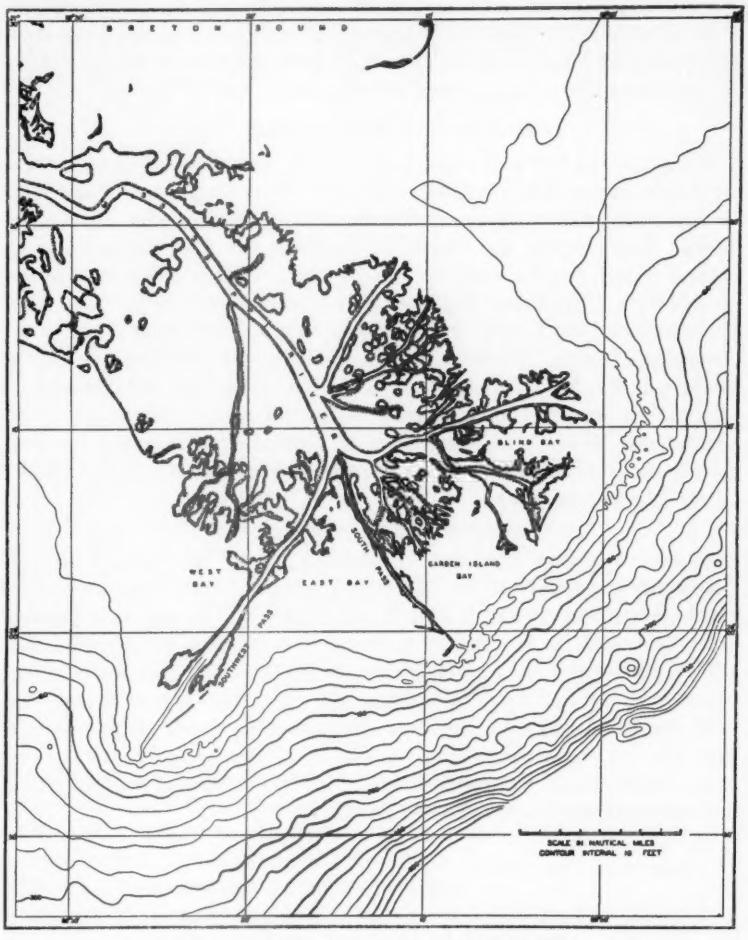

FIGURE 3.—*Marine slope outside Mississippi Delta*
From chart 1272 of U. S. Coast and Geodetic Survey. Soundings in feet.

opposed to Daly's idea. For example, under Daly's hypothesis, one would expect that where the Mississippi has built its delta across the shelf there would be ideal conditions for the development of mud currents

both because of the mud brought in by the river and because of the shallow water at the edge of the slope, with mud banks exposed to the attack of storm waves. It is, therefore, interesting to note that the soundings off the delta itself do not indicate submarine valleys (Fig. 3). Furthermore, if the Mississippi trough is characteristic of valleys cut by mud currents, either the other submarine valleys should have the same or similar shapes or they must have been formed in some other way.

LANDSLIDING AS A MODE OF ORIGIN

If the shelf in this area consists of a great submerged delta of Mississippi mud, it would be reasonable to expect the outer portion of the bank to be nicked by landslides or mud flows leaving a jagged edge. The steep frontal slope outside the Fraser River Delta has such indentations at several places, but the cases are not parallel. The indentations into the foreset beds of the Fraser Delta are only a score of feet deep. Also, these depressions off the Fraser lack the steep walls and broad flat floors of the Mississippi trough. It would be most unlikely that submarine landslides could cut into the continental shelf for 20 miles, and, furthermore, a slide in soft material could scarcely leave such steep walls as are found around the Mississippi trough (Fig. 2, Section). Nor would the scar left by the slide be likely to have a shape such as is shown by the outline of the Mississippi trough.

CAUSE OF THE STEEP SLOPES

Considerable care was taken to establish the per cent of slope at some places along the sides of the Mississippi trough. These slopes were definitely determined at 33 per cent in some places. Although it is possible for a clay bank cut recently by a stream to stand even steeper than this, such steep slopes in fine material are not stable; this is particularly true where the height of the slope is great and where the material is saturated with water. In the case under discussion, the steep slopes are almost 1000 feet high in some places (Fig. 2, Section). Accordingly, the conclusion is reached that the material holding up these slopes is relatively solid and certainly is not soft delta sediment.

"SALT" DOMES

GENERAL STATEMENT

If the steep walls of the trough are cut in solid sediment it remains to be seen why there should be anything but soft mud to represent the deposition by the Mississippi through millions of years and in a position where enormous thicknesses of delta material are known from wells on the adjacent coast. It would be unlikely that solid rock had been faulted up along the outside of the continental shelf and it would be unlikely also that there would be residual remnants of rock that had not been involved

in the general sinking of the Gulf Coast.[4] Turning to the land, one finds at least one means by which relatively solid material has been forced up into the soft sediments. That method is exemplified by the numerous

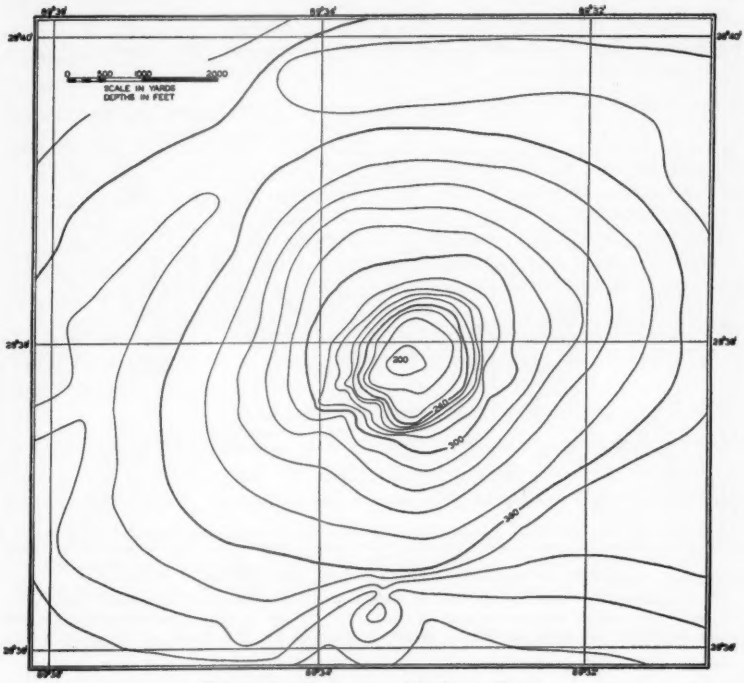

FIGURE 4.—*Dome near Southwest Pass*

Based on detailed soundings by U. S. Coast and Geodetic Survey.

salt domes of the delta area and of the coastal plains of Louisiana and Texas. Might not the salt domes also be responsible for these steep slopes on the sides of the Mississippi trough? The fact that where the sides are steepest there are either ridges or oval domes along the trough margin certainly suggests that salt domes are involved.

Another factor which must be considered in this connection is that the process of salt intrusion frequently brings up considerable quantities of resistant rock from the deeper layers. Thus the subsequent erosion might leave these rims standing above the general surroundings. It is not unlikely that some of the steep slopes and ridges around the Mississippi

[4] R. J. Russell and H. V. Howe: *Cheniers of southwestern Louisiana*, Geogr. Rev., vol. 25 (1935) p. 449.

trough were formed in this way, the salt core having been removed from the centre (Figs. 2 and 5).

A perfect example of a dome was found near the outer margin of the shelf, about 10 miles east of the submarine trough. Detailed soundings

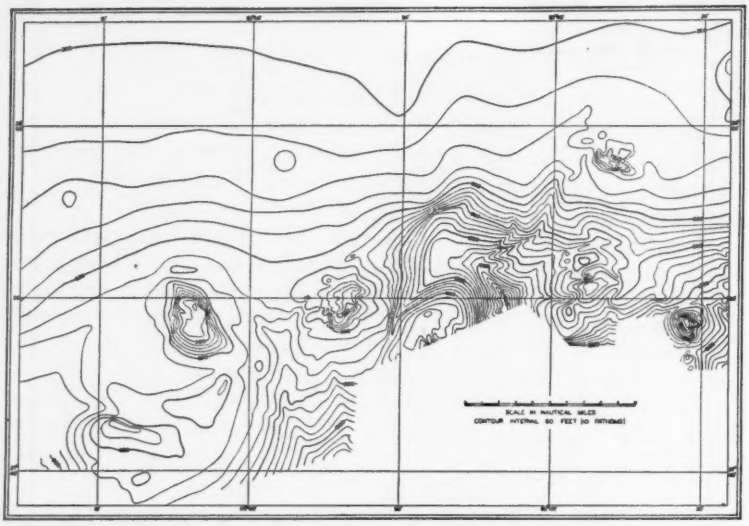

FIGURE 5.—*A group of "salt domes" and submarine valleys*

At the edge of the shelf, a little east of Galveston, Texas. Soundings around submarine valley in center and around small dome west of this valley are not numerous enough so that contours could be drawn with much confidence. Based on soundings by U. S. Coast and Geodetic Survey.

were made of this feature so that its shape is now well known. It can be seen from Figure 4 that it is certainly as round as the more symmetrical of the salt domes found on land. The comparatively flat top is in keeping with the equally flat tops revealed by drilling into salt domes along the Gulf Coast. Some of the marine domes found farther west (Fig. 5) have flatter summits.

ALGAL LIMESTONE COVER

Dredgings from the top of the salt dome shown in Figure 4 contained fragments of porous limestone mixed with abundant shells.[5] They were almost devoid of inorganic material. Portions of the limestone fragments and of the organic matrix were sent to Marcus Goldman and to J. B. Reeside for examination. Goldman stated that he found no ground for

[5] Trowbridge analyzed a sample taken from the side of this same bank and found that it consisted principally of medium-sized sand with a secondary maximum of mud [A. C. Trowbridge: *Building of the Mississippi Delta*, Am. Assoc. Petr. Geol., vol. 14 (1930) p. 981, fig. 11].

believing that the material was cap rock of a salt dome, although he thought the presence of rock in the area was suggestive of doming processes. Reeside expressed the opinion that the rock might be of recent algal growth in place. The examination of the Foraminifera in the matrix by L. G. Henbest revealed no forms that were distinctly older than the present. The forms within the rock masses were not definitely recognizable.

Subsequent examination of the specimens by J. T. Richards has led to the following comments:

"I feel quite confident that the main body of these pebbles is of Algal material which has been permeated with worm tubes. The inclusion of sand grains, mud balls, and other detrital material would in my opinion indicate that they were formed in or close to currents which would furnish these materials or that the Algae formed as a ball and was moved gently from place to place. I believe the former interpretation is probably the most logical. Another very interesting point about these pebbles is that they are incrusted with a relatively few bands of calcareous Algal material of a different nature than that of the core of the pebbles. This incrustation in my opinion indicates a static condition for the pebbles during the formation of this outer crust."[6]

POSSIBLE ORIGIN OF SALT DOME CAP ROCK

The significance of this discovery of rock on the top of the dome is increased by the report of "rock, stones, pebbles, and coral (probably bryozoa)" from records of the Coast and Geodetic Survey, based on samples taken from the tops of other domes in this area. The absence of mud upon these domes is readily explicable. Practically all ridges and hills that rise above the general level of the continental shelf are swept clean by currents.

Possibly the absence of mud may allow the growth of algal colonies forming limestone on top of the salt domes. Perhaps some of the calcareous cap rock on top of the salt domes discovered on land was formed in the same way.

DISTRIBUTION OF THE SUBMARINE DOMES

Examination of the soundings of previous surveys shows that the belt of domes can be traced definitely for 180 miles to the west-southwest of the Mississippi submarine trough (Fig. 6). Farther west the soundings are scarce, but they indicate several submarine domes, the most westerly one being well within the shelf margin east of Corpus Christi and south of Port O'Connor. These last are based on single soundings and are therefore subject to great uncertainty. On the other hand, there is no indication that the domes exist to the east of the Mississippi Delta.

Altogether, at least 26 submarine domes have been recognized. All lie either near the outside of the continental shelf or on the upper portion of

[6] Personal communication.

the continental slope.[7] They are not evenly spaced, as there is some tendency for them to be concentrated around each of the submarine valleys which are distinguishable along the shelf edge. These can be located on Figure 6 by observing the inbends of the 600- and 1200-foot contours.

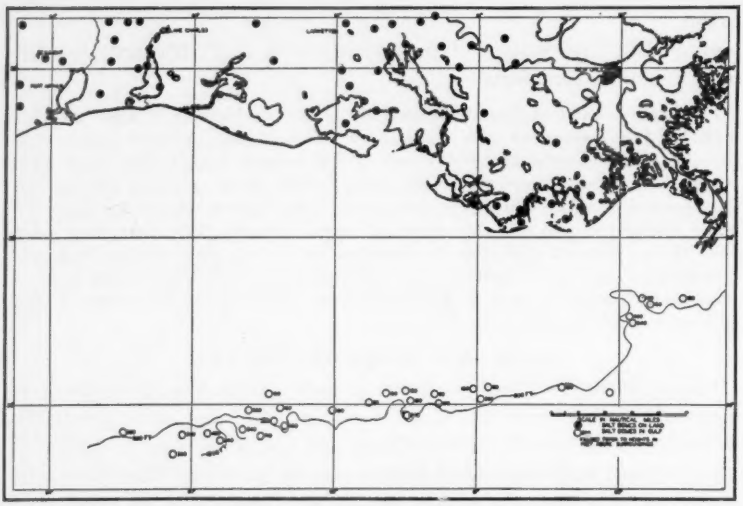

FIGURE 6.—*Distribution of domes on the sea floor*

West of Mississippi Delta and of buried domes on adjacent land. Figures show height of domes in feet above surrounding portions of the ocean bottom. Most domes on land have been discovered by geophysical methods and do not have topographic expression. Based on soundings by U. S. Coast and Geodetic Survey and information from various oil journals and other publications. Data taken from Coast and Geodetic Survey chart 1116.

The group of buried salt domes which crosses southern Texas and Louisiana terminates at the outer end of the Mississippi Delta. The submarine salt domes also terminate at about this point, making the apex of a large recumbent V.

EXPLANATION OF DOME ALIGNMENT

The buried salt domes on land are spread over a much wider area than are the known protruding domes of the sea floor. Although there is no reason to believe that buried domes do not extend beyond the coast, the somewhat linear distribution of the domes at the shelf margin suggests that the latter may be concentrated along a fault zone which has also been

[7] Objection to this statement might be made on the grounds that Sabine Bank and Heald Bank could be salt domes. However, the shape of these banks suggests that they are submerged offshore bars like Trinity Shoal and Ship Shoal, which lie farther east.

responsible for determining the outer edge of the continental shelf. An alternative explanation for the distribution would be that the processes of erosion and deposition have brought into relief the domes at the shelf edge, but have removed or covered those on the shelf inside. It is not easy to decide between these two suggestions; especially as it is not known whether the domes extend well down the slope and out onto the deep ocean floor, because there are few soundings at great depth. There are, incidentally, two elevations on the deep slope off Galveston which may be of salt dome origin.

The evidence of sea-level lowering during the glacial epochs favors the interpretation that the domes have topographic relief because of their position; for even in the late Wisconsin stage there should have been sufficient lowering to have allowed the waves to attack any dome that had been pushed up above the shallow shelf inside. Therefore, unless there had been doming action causing upbending of the sea floor since the last great glaciers melted, the salt domes with surface relief should be confined to the deeper water.

On the other side of the picture, however, is the fact that at least one dome on the outer shelf rises to less than 100 feet from sea level. This one would certainly have been attacked by the waves of the late-Wisconsin glacial stage. One also might hypothesize a fault zone at the outer edge of the shelf, for the following reasons:

(1) The straightness of continental slopes in general and of this slope in particular suggests that they are delimited by faults.

(2) The lack of any pronounced outbend of the continental slope off the Mississippi Delta where deposition might be supposed to have extended the shelf seaward suggests that the edge has been maintained by faulting.

(3) Continental shelves in general are too steep to be explicable as the result of building out by deposition of fine sediment. This slope, however, does not conform with most of the others in this regard.

(4) Off many coasts there is evidence of the presence of rock bottom both at the outer edge of the continental shelves and on the sides of canyons cut into the upper portion of the continental slopes. This also is an argument against the hypothesis that continental shelves are built out by deposition; it thus favors the fault origin for continental slopes.

HEIGHT OF INTRUSION RELATED TO CONCENTRATED FLOW

Although the submarine domes may not be more closely spaced than the domes on the adjacent land, they have been pushed much closer to sea level. Most of those on land are found at considerable depth. Nothing is yet known about the deeply buried domes of the sea bottom, but this

greater aggregation of relatively high domes is perhaps explained by the concentration of the salt flow from over an extensive area into the narrow belt at the shelf edge, where access may have been possible because of the presence of a fault zone. It might also be possible that the supposed subsidence of the Mississippi geosyncline [8] was greater shoreward of the shelf margin. This would cause the salt beds to be nearer the surface and to have a dip that would favor the intrusion process at the margin.

SALT DOMES AS THE CAUSE OF THE CANYONS

It could be asked with good reason whether the domes might not be the cause of the submarine valleys along this part of the coast. For example, between two domes pushed up on the continental slope, there should be a valley-like depression. Possibly some of the valleys shown in Figure 4 may be of this origin. On the other hand, there are decided objections to this explanation for the large Mississippi trough. An outward-sloping valley depression between domes could not be produced on the continental shelf, and the bottom of such a valley should not ordinarily sink far below the general level of other parts of the continental slope at equal distances beyond the shelf margin. Thus, no deep shelf and slope indentation such as the Mississippi trough could be explained in this way. The trough extends 20 miles inside the shelf margin and 10 miles inside the belt of salt domes. Furthermore, the outer trough cuts deeply into the continental slope.

RELATION OF SUBMARINE VALLEYS TO DOMES

There are two possible explanations for the greater concentration of domes around the submarine valleys than elsewhere. In the first place, if submarine valleys were cut into all parts of the continental slope and outer shelf, the valleys would have a better chance to persist where their sides were held up by the relatively resistant salt domes instead of by the soft Mississippi muds. Therefore, more canyons would now be found in relation to the domes. Secondly, the presence of synclinal depressions between salt domes, making for interdomal depressions, like those described by Ritz,[9] might have led to the localization of the principal submarine valleys. This would be particularly likely if the mud were washed completely away from the dome covers, but it might also be true if a relative sinking of the area between the domes had begun before the time of sea-level lowering.

Another way in which the domes may have influenced the submarine valleys is through the solution of the salt cores leaving as erosion remnants

[8] H. V. Howe: *Stratigraphic evidence for Gulf Coast geosyncline*, Geol. Soc. Am., Pr. 1935 (1936) p. 82.

[9] C. H. Ritz: *Geomorphology of Gulf Coast salt structures*, Am. Assoc. Petr. Geol., Bull., vol. 20 (1936) p. 1413-1438.

the resistant rocks dragged up along the sides. These solution cavities might have been utilized by the rivers in developing their courses. The branch of the Mississippi trough which extends southwest (Fig. 2) from the main valley might have had such an origin. Against the idea of solution as an important factor may be cited the lack of any substantial evidence of basin depressions in the area.

If the submarine canyons were caused by river erosion during a great drop in sea level, which seems to be the only explanation that will fit the newly acquired information, then the streams flowing out over the edge of the shelf would have cut rapidly into the muddy deposits of the Mississippi drainage. In removing this mud, any salt domes near the surface would have been exposed and these would probably have withstood erosion better than the mud, particularly if they had insoluble cap rocks. This may help explain the relief of some of the domes on the continental slope.

SUMMARY AND CONCLUSIONS

The large trough-shaped submarine valley, penetrating 20 miles into the Gulf Coast continental shelf, is off the main delta of the Mississippi River, well to the southwest of the outer "Bird Foot" Delta. This suggests that if the valley is of subaerial origin, it is probably older than this outer delta. The flat floor of the submarine valley, which is in contrast to the V-shape of most submarine canyons, is explained on the basis of a great mud-fill from the Mississippi River. The steep walls of the trough are thought to be due to salt domes which, perhaps because of their cap rock, resisted the erosion of the low sea-level stage when the submarine valleys were cut. It seems reasonable that if it had not been for these bordering salt domes, the walls of the valley would have slumped until only gentle slopes were left.

The salt domes are not only related to the outer portion of the Mississippi submarine trough, but they are found also all along the outer edge of the continental shelf for at least 180 miles west of the Mississippi Passes. It is thought that their concentration in this narrow belt may be the result of upward migration of the salt along a fault zone. The great relief of these domes, which is in contrast to those found on the Gulf Coast, may be due partly to the failure of erosive processes to interfere with the bulging of the bottom and partly to the removal of fine sediments from around them during the time when the submarine valleys were being cut into the shelf margin.

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